

THE EFFECT OF MODERATE PARKINSON'S DISEASE ON THE BIOMECHANICS OF  
COMPENSATORY BACKWARDS STEPPING

By

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## *ABSTRACT*

Postural instability leading to falls is one of the major unmet needs in the treatment of Parkinson's disease (PD). The progression of postural instability is not well understood, and a better understanding of the biomechanics underlying the progression of postural instability may be instrumental in the development of more sensitive clinical measures of postural instability and fall risk in PD. The biomechanical analysis of the response to a balance perturbation provides an opportunity to better understand postural instability in PD. This study examined the compensatory stepping response to a backwards pull in participants with moderate PD compared to age-range matched healthy controls. The first study investigated the overall response to a balance disturbance in moderate PD, and found that patients with moderate PD utilized more steps to regain balance, had a longer weight shift time, and used a base-width neutral step as a strategy to regain balance, compared to controls. The second study further investigated the compensatory response by focusing on the preparation phase and found that participants with moderate PD used multiple anticipatory postural adjustments (APAs), resulting in longer liftoff times and significantly different movement in the center of pressure prior to liftoff compared to healthy controls. The third study investigated the effects of PD and step strategy (single step, multiple steps, and a base-width neutral step) on balance recovery and found that participants with moderate PD took significantly longer to recover balance, and that the type of strategy used to respond to the disturbance significantly impacted recovery time. Additionally, the use of a base-width neutral step as the first step in the response emerged as a strategy that has not been previously documented and significantly delays balance recovery. These results suggest that moderate PD significantly impairs the compensatory response to a backwards pull. Furthermore, this impairment could be attributed to a delay in the preparation phase of the step response. This delay was associated with the use of multiple anticipatory postural adjustments and/or the use of a base-width neutral step as the first step in the response. Further

study should examine the progression of impairment in these compensatory responses across PD severity levels, and the correlation with fall risk.

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## CHAPTER ONE: INTRODUCTION

### *Background and Motivation*

Parkinson's disease (PD) is a neurodegenerative disorder estimated to affect about 350,000 people in the United States and about 4.5 million in the world (Olanow, Stern, & Sethi, 2009). Postural instability leading to falls is one of the most disabling symptoms of Parkinson's disease and greatly increases the risk of falling- so much that up to 70% of people with PD fall in a given year (Wood, Bilclough, Bowron, & Walker, 2002). Falls have devastating effects on quality of life including fractures, hospitalization, loss of independence, and restriction of activities (Bloem, van Vugt, & Beckley, 2001; Gray & Hildebrand, 2000; Lachman et al., 1998; Pickering et al., 2007; Tinetti, de Leon, Doucette, Baker, & Dorothy, 1994). Interventions to reduce fall risk are most effective if they are implemented before someone falls, but the current clinical assessments for postural instability in PD are not sensitive enough to track the development of postural instability prior to a fall (Munhoz et al., 2004; Visser et al., 2003). While progress has been made in identifying clinical and physiological parameters that can more accurately predict fall risk (Duncan et al., 2012; Kerr et al., 2010; King, Priest, Salarian, Pierce, & Horak, 2012; Latt, Lord, Morris, & Fung, 2009), there is still a need to assess postural instability throughout the disease progression so that appropriate interventions can be introduced at appropriate times. Laboratory-based experiments may provide the missing link in fall-risk factor development.

It is well established that falls occur for multi-factorial reasons due to the complex interplay of multiple balance systems, medications and physiological changes, and musculoskeletal strength and range of motion. As of 2007 however, no one had developed any fall risk assessment tool that predicted falls any better than a history of falls (Bloem, Grimbergen, Cramer, Willemsen, & Zwinderman, 2001; Pickering et al., 2007). More recently, exciting advances have been made in the development of more

comprehensive fall risk assessment tools and the addition of more sensitive laboratory based measurements are clearly important in this development.

Clinical assessment of postural instability is done with the retropulsion test. In this test, which is part of the United Parkinson's Disease Rating Scale (UPDRS) evaluation, the clinician provides a sudden backwards pull to the patients' shoulders and visually assesses the resulting balance response. Issues associated with this test include problems with reliability in executing and a lack of sensitivity in scoring the test, and it is not predictive of fall risk (Bloem, Grimbergen, et al., 2001; Horak, Dimitrova, & Nutt, 2005; Robinson et al., 2005; Visser et al., 2003).

Recently, more quantitative laboratory tests have shown promising results in detecting postural instability *earlier* in the progression of PD. In fact, a recent prospective study showed that measures of anterior-posterior sway while standing on a firm and foam surface was the *only* measure among a wide variety of demographic, clinical, and disease-specific tests that discriminated new fallers who fell for the first time in the 6 month study period (Kerr et al., 2010). This exciting development confirms the idea that balance-related biomechanical parameters are important in describing postural instability early in disease progression.

### *Specific Aims*

The long-term goal of this work is to contribute towards the development of quantitative clinical assessments for postural instability and fall risk that effectively predict potential falls prior to a patient's first fall. In our previous study, we have demonstrated that balance recovery parameters, based on the biomechanical analysis of body segment kinematics, kinetics, and muscle activities during the response to a balance disturbance, show promise in effectively detecting early signs of postural instability in those with *mild* PD (McVey et al., 2009), a group which by definition has no clinically detected postural instability. Further research is needed to investigate whether or not these balance recovery parameters are sensitive to disease progression and fall history and useful in assessing fall risk.

The primary goal of this work is to investigate the relationship between postural control and *moderate* PD. The first study investigates the overall response to a balance disturbance in moderate PD, looking at strategy, temporal, kinematic, and center of pressure parameters during the first step in the response. The second study further investigates this response by focusing on the center of pressure movement and the use of anticipatory postural adjustments during the preparation phase of the response. The third study investigates the use of a base-width neutral step as the first step in the response in the PD participants, and the effects of this strategy on balance recovery.

### *Dissertation Content*

This document contains six chapters. Chapter 1 consists of an introduction to the area of study. Chapter 2 consists of an extensive background survey of relevant literature published. Chapter 3 consists of a manuscript reporting the background, methods, and results of the study investigating the effects of moderate Parkinson's disease in the step response to a backwards pull. Chapter 4 consists of a manuscript reporting the background, methods, and results of the study investigating the effects of moderate Parkinson's disease on the preparation phase of the step response. Chapter 5 consists of a manuscript reporting the background, methods, and results of the study investigating the effects of the use of a base-width neutral step on balance recovery in moderate PD. Chapter 6 consists of a summary of this body of work.

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## *CHAPTER TWO: BACKGROUND*

### *Parkinson's Disease*

Parkinson's disease (PD) is a neurodegenerative disorder first described by James Parkinson in 1817 and is estimated to affect about 350,000 people in the United States and about 4.5 million in the world (Olanow, Stern, & Sethi, 2009). These numbers are expected to rise to between 8.7 – 9.3 million people in the world in 2030 (Dorsey et al., 2007). PD is more prevalent in men than women, and its prevalence increases with age. There are currently no other risk factors or accurate predictors of who is at risk, although it has been shown to have a higher prevalence rate in developed countries. It is well accepted that both genetic components and environmental factors contribute to the likelihood of developing PD (Wirdefeldt, Adami, Cole, Trichopoulos, & Mandel, 2011), although the evidence is varied as to which factors and what role they play in disease development. PD progressively affects mobility and independence, ultimately resulting in an increase in mortality rate of 2-5 times (Louis, Klatka, Liu, & Fahn, 1997). Current drug therapies help patients deal with the symptoms of PD, but there is no treatment that slows or stops the progression of the disease.

*Diagnosis.* Diagnosis for PD is given through examination by a neurologist or movement disorders specialist. The presence of a resting tremor, asymmetry of symptoms, and a positive response to Levodopa therapy are an indication of the presence of Parkinson's disease. Physiologically, PD is characterized by the progressive death of dopaminergic neurons in the basal ganglia, specifically in the pars compacta of the substantia nigra (Hickey & Stacy, 2011). It is estimated that 60-70% of these neurons have already been lost at the onset of symptoms (Lang & Lozano, 1998b).

*Severity Rating Scales.* Parkinson's disease is a progressive disease, and there are two severity rating scales currently in use to quantify its progression: The Unified Parkinson's Disease Rating Scale

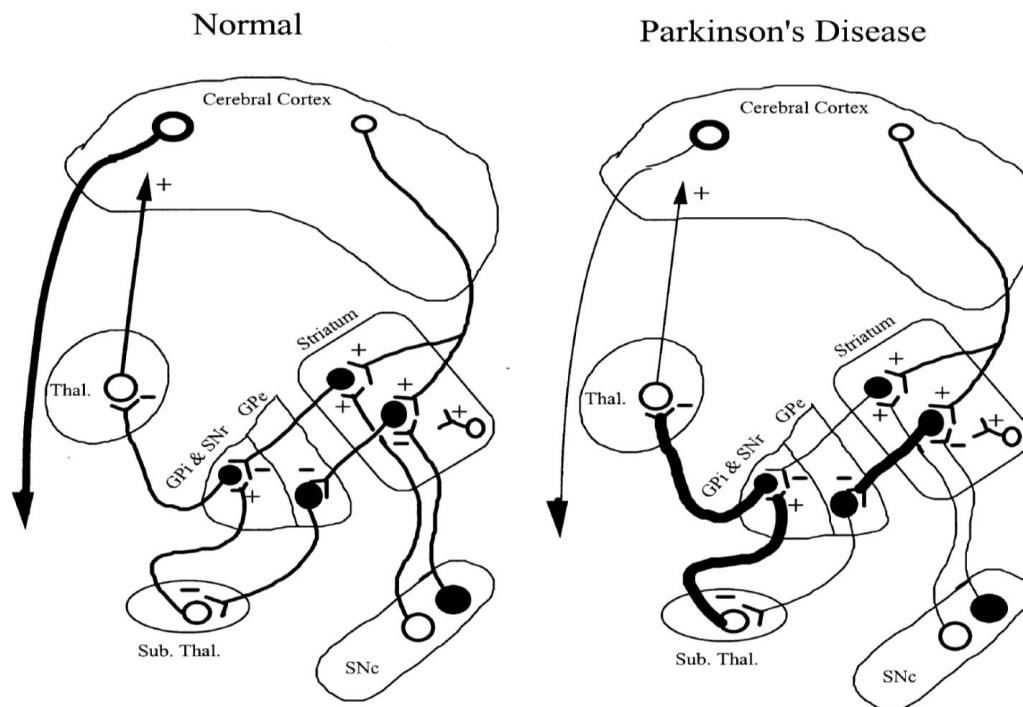
(UPDRS) and the Hoehn and Yahr scale. The Hoehn and Yahr scale was developed in 1967 by Margaret M. Hoehn, MD and Melvin D. Yahr, MD. The Hoehn and Yahr scale consists of 5 stages to assess the degree of disability due to Parkinson's symptoms (Hoehn & Yahr, 1998):

- Stage 1:* Unilateral involvement, minimal or no functional impairment.
- Stage 2:* Bilateral or midline involvement, without impairment of balance.
- Stage 3:* First sign of impaired righting reflexes possibly seen as unsteadiness as the patient turns, or loss of balance when pushed from standing with eyes closed and feet together. Functionally restricted in activities, possibly still able to work, physically capable of being independent, disability is mild to moderate.
- Stage 4:* Fully developed, severely disabling disease; patient is still able to walk and stand unassisted but is markedly incapacitated.
- Stage 5:* Confinement to bed or wheelchair unless aided.

The Unified Parkinson's Disease Rating Scale was developed in 1987 and consists of 3 sections: a mentation, behavior and mood section; an activities of daily living section; and a motor section. In each section, the examiner scores the patient on a scale of 0-4 on several questions, with 0 being normal and 4 representing the worst possible case for that question. The motor section consists of questions for the patient as well as several quick physical tests such as finger taps, rising from a chair, a postural stability test (called the retropulsion test or pull test), and rigidity tests where the examiner passively moves the limbs to assess rigidity. The scores for each question are added to determine the total score, with the maximum being 200. Scores are not typically given to the patient, but are used by the clinicians to track the progression of the disease.

### *Pathophysiology*

*Anatomy of the Basal Ganglia.* The basal ganglia are located beneath the cerebral cortex and consist of five nuclei: the *globus pallidus*, *caudate nucleus*, *putamen*, *subthalamic nucleus*, and *substantia nigra*. The globus pallidus is divided into an internal and external region, and the substantia nigra is



**Figure 2-1. Abnormalities in neural activity in Parkinson's Disease.**

Notice that abnormalities in activity in basal ganglia structures lead to increased inhibitory activity in the thalamus, leading to decreased excitatory input to the cerebral cortex and suppression of the motor cortical areas. Thal: thalamus; GPi/GPe: globus pallidus internal/external; SNr/Snc: substantia nigra pars reticulata/pars compacta; Sub. Thal: subthalamic nucleus. Plus (+) indicates excitatory connection, minus (-) indicates inhibitory connection. In right figure, bold black lines indicate increased activity, thin lines indicate reduced activity. *Figure courtesy of Dr. Paul Cheney.*

divided into two regions: the dorsal (pars compacta) and ventral (pars reticulata) regions. The caudate nucleus and putamen are often referred to together as the *striatum* (Kandel, Schwartz, & Jessell, 2000; Latash, 1998).

*Function of the Basal Ganglia.* The basal ganglia are thought to be indirectly involved in movement by both the facilitation (allowing) and the inhibition (disallowing) of movement, perhaps in the role of focusing movements through the balance of facilitation and inhibition (Wichmann, DeLong, Guridi, & Obeso, 2011). For a movement to occur agonist muscles must be sufficiently activated and the antagonist muscles must be inhibited. The basal ganglia are also important in preparing the body for



voluntary movement as they process information needed for planning, initiating, and organizing the postural adjustments prior to movement, and are also involved in sequencing movements and motor learning (Kandel et al., 2000; Latash, 1998). Finally, the basal ganglia are thought to be involved in adjusting an in-process movement to an unexpected event (Marsden & Obeso, 1994; Wichmann et al., 2011).

*Neurophysiology of the Basal Ganglia.* While the basal ganglia use several neurotransmitters, they contain 80% of the total dopamine in the brain. Parkinson's disease is caused by the death of these dopaminergic neurons that project between the striatum and the substantia nigra pars reticulata (Kandel et al., 2000; Latash, 1998). Loss of these projections causes increased activity in subthalamic nucleus neurons which leads to suppression of thalamic activity, ultimately leading to suppression of cortical motor areas. By the onset of symptoms in Parkinson's disease, 60-70% of the dopaminergic projections have been lost in the ventrolateral tier of substantia nigra pars compacta (Lang & Lozano, 1998a). Figure 2-1 illustrates the basal ganglia circuitry and what is different in Parkinson's disease.

The basal ganglia receive input at the striatum from the cerebral cortex, thalamus, and brain stem. Output from the basal ganglia leaves from the globus pallidus internal (GPi) region or the substantia nigra pars reticulata (SNr) region (Wichmann et al., 2011). The main output is to the cerebral cortex via the thalamus although it also outputs to the brain stem. The basic basal ganglia-thalamo-cortical loop consists of input from cerebral cortex → striatum → GPi and/or SNr → output to thalamus. All output from the basal ganglia is inhibitory. This loop is somatotopically organized, so that certain parts of the cortex project to certain parts of the striatum (Kandel et al., 2000; Latash, 1998).

There are thought to be two main pathways through the basal ganglia. The *direct pathway* is thought to facilitate movement through the inhibition of the GPi and SNr neurons, which results in reduced inhibition of thalamocortical projections, and the facilitation of movement. The *indirect pathway* is thought to suppress movement by increasing the inhibitory output of the basal ganglia. There is another pathway called the *hyperdirect pathway*, which also results in increased inhibitory output and suppressed movement, however this loop works faster than the indirect pathway (Wichmann et al., 2011).

### *Symptoms of Parkinson's Disease*

The loss of dopaminergic input from the substantia nigra pars reticulata causes increased activity in the indirect pathway (which inhibits movement) and decreased activity in the direct pathway (which facilitates movement). Both of these situations lead to decreased activity of the motor cortex, leading to the common symptoms of Parkinson's disease.

*Bradykinesia.* Bradykinesia refers to slowed and sometimes incomplete movements. Akinesia refers to a failure of willed movement to occur (Hallett, 2003). Bradykinesia is physiologically defined as a failure to energize muscles to a level sufficient to complete a movement in a reasonable amount of time, and movement is especially slow in sequenced movements. Akinesia is physiologically defined as a prolongation of reaction time- a muscle is selected but not activated, especially seen in initiating voluntary movement (Hallett, 2003). In PD, bradykinesia and akinesia are seen in the expressionless appearance of the face, shuffling gait, and difficulty initiating movements (Latash, 1998). These are thought to be due to the loss of the dopaminergic neurons in the direct pathway, resulting in increased inhibition of the motor cortex (Kandel et al., 2000; Latash, 1998).

*Tremor and Rigidity.* Parkinson's disease is characterized in part by a resting tremor at about 4-6 Hz. Rigidity is manifested as an increased muscle tone resulting in resistance to passive movements. These are examples of abnormal motor activation due to input from affected projections in the indirect pathway (Hallett, 2003; Kandel et al., 2000; Latash, 1998). Physiologically, rigidity can be caused by a change in muscle properties or joint characteristics, the amount of background contraction of the muscles, and the magnitude of the stretch reflex. In PD all three are affected (Hallett, 2003).

*Postural Instability.* Postural instability refers to the impaired balance and coordination often seen in those with Parkinson's disease. Postural stability requires proper sensory organization, appropriate motor adjustments to prepare, execute, and adjust a movement, and appropriate background muscle tone (Horak, Nutt, & Nashner, 1992b). Patients with PD often have abnormal postural preparations prior to a voluntary movement, have increased sway when standing still, use abnormal and ineffective postural

reactions to an external perturbation, and are less able to adapt a postural response to a change in support or environmental conditions (Burleigh-Jacobs, Horak, Nutt, & Obeso, 1997; Chong, Horak, & Woollacott, 2000; Horak et al., 1992b; King, St George, Carlson-Kuhta, Nutt, & Horak, 2010; Nutt, Horak, & Bloem, 2011). Postural instability combined with other PD symptoms leads to an increased risk of falling in those with Parkinson's disease.

### *Therapy*

There are currently no treatments that have been shown to slow or stop the progression of Parkinson's disease. However, therapies do exist that improve the motor complications associated with the disease.

*Levodopa and Drug Therapy.* Levodopa is still the most effective drug therapy for PD. Introduced over 40 years ago, Levodopa is a dopamine therapy, working to replace dopamine that has been lost in the brain. Levodopa reduces the severity of PD symptoms such as bradykinesia, rigidity and tremor, and is effective initially in over 90% of patients (Lang & Lozano, 1998a, 1998b).

While Levodopa is very effective early on in disease progression, complications begin as its use becomes more long-term. Complications such as dyskinesias, motor fluctuations (responding normally to the medication for a period, followed by periods of minimal response), and wearing off occur in about 50% of patients who use the drug for 5 years or more, and in about 80% of patients who use the drug for 10 years (Hickey & Stacy, 2011; Koller & Tse, 2004).

Another concern is that several symptoms of PD do not respond to Levodopa treatment. In particular, motor deficits such as postural instability, freezing of gait, and swallowing problems have been shown to be resistant to Levodopa treatment (Bronte-Stewart, Minn, Rodrigues, Buckley, & Nashner, 2002; Koller & Tse, 2004). In a postural sway study by Rocchi *et al.* it was shown that Levodopa treatment actually increased abnormalities in sway, and subjects performed better when off medication (Rocchi, Chiari, & Horak, 2002). In addition, in a study on the effects of Levodopa, subjects receiving the

highest dose had significantly more dyskinesia, hypertonia, infection, headache, and nausea as compared to controls on placebo (Fahn et al., 2004).

Other types of drug therapies are being used to treat PD as well. Non-dopaminergic therapies such as Adenosine A2A Agonists and Monoamine Oxidase B inhibitors help to reduce the side-effects of Levodopa and show potential neuroprotective effects, respectively (Hickey & Stacy, 2011). Dopamine agonists are also used and have less risk of motor fluctuations but a higher incidence of side effects (Hickey & Stacy, 2011).

*Deep Brain Stimulation.* Deep Brain Stimulation (DBS) has become a very effective alternative to Levodopa therapy for treating PD. In fact, it is *more* effective at treating motor problems and improving quality of life in patients with motor fluctuations (Weaver et al., 2009). This treatment involves high frequency stimulation through electrodes placed most often in the subthalamic nucleus or globus pallidus internal of the basal ganglia. More recently, stimulation of the pedunculopontine nucleus has been discovered as a target to improve postural instability (Hickey & Stacy, 2011). The advantages over Levodopa therapy most likely stem from the fact that DBS can affect non-dopaminergic pathways, which are thought to be increasingly affected by Parkinson's disease (Rocchi, Chiari, Cappello, Gross, & Horak, 2004). However, only about 5% of PD patients meet the criteria to be eligible for DBS (clinically diagnosed idiopathic PD, experiencing disabling motor fluctuations, no signs of dementia, and currently responsive to Levodopa treatment), so it is not a widespread therapy (Hickey & Stacy, 2011).

### *Postural Instability*

Postural control is described by the center of mass, center of pressure, and base of support. The center of pressure is the point where the resultant ground reaction force for the body acts. The base of support is the area circumscribed by the support surface (the feet when standing). The center of pressure changes constantly to account for the change in location of the center of mass. For stability, the center of mass should not leave the base of support, so the center of pressure constantly moves around to keep the center of mass within the base of support (Latash, 1998).

The brain receives and processes different types of cues about the position of the body and its stability from several different systems. The vestibular system provides signals related to the orientation and movement of the head in space via organs in the inner ear. The somatosensory system provides signals gathered from the skin and deep pressure sensors in the body and includes touch, pain, pressure, temperature, and proprioception (Buchanan & Horak, 2003; Latash, 1998). Visual information is another source of postural information. Postural stability requires the proper processing of information from all of the sensory systems, appropriate motor adjustments to prepare, execute, and adjust a movement, and appropriate background muscle tone (Horak, Nutt, & Nashner, 1992a).

*Falls in Parkinson's Disease.* Falls have a devastating impact on quality of life and Parkinson's disease greatly increases the risk of falling. The 3 month fall rate is almost 50% in PD (Pickering et al., 2007), and the yearly fall rate has been estimated to be as high as 70% (Wood, Bilclough, Bowron, & Walker, 2002). This is significant because falls have devastating effects on quality of life including fractures, hospitalization, loss of independence, and restriction of activities (Bloem, van Vugt, & Beckley, 2001; Gray & Hildebrand, 2000; Lachman et al., 1998; Pickering et al., 2007; Tinetti, de Leon, Doucette, Baker, & Dorothy, 1994). In a retrospective study of 1,092 Parkinson's patients by Wielinski *et al.*, 65% of those who fell sustained an injury, 22% of those who fell sustained a fracture, and 41% of those sustaining fractures required surgery. Notably, 27% of the entire study group required health care services as a result of falling. This indicates substantial costs associated with falling in Parkinson's disease (Wielinski, Erickson-Davis, Wichmann, Walde-Douglas, & Parashos, 2005). Other studies have echoed this increased risk of falling and increased risk of injury in Parkinson's disease (Balash et al., 2005a; Contreras & Grandas, 2012). In addition to the severe consequences of injurious falls, a fear of falling (with or without a previous fall) has been shown to be associated with increased fall risk as well as indicating a reduced quality of life in older adults (Adkin, Frank, & Jog, 2003; Mak & Pang, 2009; Tinetti et al., 1994).

*Fear of Falling.* Fear of falling is even more prevalent in Parkinson's disease than in the general elderly population and may or may not stem from actually experiencing a fall (Adkin et al., 2003; Tinetti

et al., 1994). This fear can have a significant impact on quality of life as well as on the risk of falling. In addition to added general stress, fear of falling impacts quality of life by causing the person to restrict physical and social activities in which they would normally participate (Tinetti et al., 1994). Tinetti *et al.* developed the Falls Efficacy Scale in order to more precisely determine the relationship between fear of falling and actual functioning. They found that falls efficacy was strongly associated with tests of functioning and that a person's perception of capability influences behavior, regardless of the actual capability. In addition, they found that about 15% of subjects who had never fallen reported a decrease in activity due to a fear of falling, indicating an unnecessary decline in quality of life (Tinetti et al., 1994).

In addition to the quality of life impacts, fear of falling has also been associated with an increase in fall risk, especially in Parkinson's disease (Bloem, Steijns, & Smits-Engelsman, 2003; Evitt & Quigley, 2004; Mak & Pang, 2009; Murphy, Dubin, & Gill, 2003; Robinson et al., 2005). This may be due to the decrease in activity, a change in postural stability due to increased caution, or a change in balance strategy. The exact interaction between fear of falling and postural instability is still unknown.

*Assessment of Fall Risk in PD.* It is well established that falls occur for multi-factorial reasons due to the complex interplay of multiple balance systems, medications and physiological changes, and musculoskeletal strength and range of motion. Previously, multiple studies have determined several individual factors that are associated with an increased risk of falling in PD- specifically a history of previous falls, increased disease severity and duration, depression, dementia, and urinary incontinence (Ashburn, Stack, Pickering, & Ward, 2001; Balash et al., 2005b; Bloem et al., 2003; Gray & Hildebrand, 2000; Wood et al., 2002). In addition, the following factors have also been associated with a history of falls: the presence of dyskinesias, freezing episodes, loss of arm swing, fear of falling, poorer scores on several measures of the UPDRS test, poor performance on clinical measures of motor planning, fine motor control, limb coordination, and gait (Ashburn et al., 2001; Balash et al., 2005b; Dennison et al., 2007; Gray & Hildebrand, 2000; Matinoli et al., 2007; Robinson et al., 2005; Wood et al., 2002). As of 2007 however, no one had developed any fall risk assessment tool that predicted falls any better than a history of falls (Bloem, Grimbergen, Cramer, Willemsen, & Zwiderman, 2001; Pickering et al., 2007).

More recently, exciting advances have been made in the development of more comprehensive fall risk assessment tools and the addition of more sensitive laboratory based measurements are clearly important in this development.

Laboratory-based experiments may provide the missing link in fall-risk factor development, as a recent study demonstrated the postural sway component of a clinical balance test to be the only measure among a wide variety of clinical tests that was significantly different between a group of non-fallers with PD and a group of previous non-fallers with PD who experienced their first fall in the 6 month study period (Kerr et al., 2010). In addition, the recently developed Balance Evaluation Systems Test (BESTest), the most comprehensive evaluation available to date, includes components derived from laboratory sway and balance tests (Horak, Wrisley, & Frank, 2009).

The (BESTest) was recently proposed by Horak *et al.* as a comprehensive fall risk assessment tool (Horak et al., 2009). This is a clinical test that evaluates 6 different balance components: 1) Biomechanical Constraints (base of support, center of mass alignment, ankle strength and range of motion, hip/trunk lateral strength, sit on floor and stand up), 2) Stability Limits/Verticality (sitting verticality and lateral lean, functional reach forward, functional reach lateral), 3) Anticipatory Postural Adjustments (sit to stand, rise to toes, stand on one leg, alternate stair touching, standing arm raise), 4) Postural Responses (feet-in-place response forwards and backwards, compensatory stepping, backwards and lateral), 5) Sensory Organization (sensory integration for balance test- evaluating sway during stance on a firm surface with eyes open and eyes closed, and stance on a foam surface with eyes open and eyes closed), and 6) Stability in Gait (level surface gait, change in gait speed, walking with head turns, walking with pivot turns, stepping over obstacles, “Timed Up and Go” test, “Timed Up and Go” test with dual task).

The advantages of this test are that it not only evaluates several of the different types of balance impairments that may exist and lead to falls, it can also give physical therapists direction as far as where to focus therapies to improve balance and reduce fall risk. It has been shown to be more sensitive than the Berg Balance Scale and the Functional Gait Assessment (Leddy, Crowner, & Earhart, 2011), and to be

effective at identifying fallers within 6 months of a fall, but not at 12 months (Duncan et al., 2012). The disadvantages of this test are that it is time intensive- it takes a full 30 minutes for a trained physical therapist to administer the test, and some of the evaluation points such as “sway on a hard surface” are hard to visually measure outside of a laboratory (Horak et al., 2009). This test scores each component on a scale from 0 (worst) to 3 (best). This is by far the most comprehensive balance assessment tool available however, it was really designed for the physical therapist to use in determining specific balance training for individuals. There is still a need for a more diagnostic fall risk tool that will allow clinicians to refer patients at certain levels of fall risk to see a physical therapist and begin the more intense balance assessments.

*Assessment of Postural Instability.* Postural instability is one of the cardinal symptoms of Parkinson’s disease and ultimately leads to falls (Michalowska, Fiszer, Krygowska-Wajs, & Owczarek, 2005). The retropulsion test (sometimes called the pull test) is widely used to assess postural instability in Parkinson’s disease. In this test, which is part of the United Parkinson’s Disease Rating Scale (UPDRS) evaluation, the clinician provides a sudden backwards pull to the patient’s shoulders and visually assesses the resulting balance response. Problems associated with this test include problems with reliability in executing and scoring the test. For example, some examiners warn patients about the pull and perform it several times, while others provide no warning and perform it only once. The patient’s response is scored on a course scale of 0-4 defined as follows: 0: normal, 1: recovers unaided, 2: would fall if not caught, 3: unstable, loses balance spontaneously, 4: unable to stand unassisted. The rating scale does not have a specific definition of a normal response or a cutoff response that indicates high fall risk. It is implied that those at a higher risk of falling require more steps to maintain their balance, while those at a lower risk require fewer steps. This test has been shown to be sensitive to differences between PD patients with and without a history of falls, however most of those studies involve severe cases of PD who already exhibit major balance problems and it is not predictive of fall risk (Bloem, Grimbergen, et al., 2001; Horak, Dimitrova, & Nutt, 2005b; Robinson et al., 2005; Visser et al., 2003).



Recently, more quantitative laboratory tests have shown promising results in detecting postural instability *earlier* in the progression of PD. One study of 55 subjects with mild-moderate PD showed that an increased medial-lateral sway and increased sway area were associated with increased postural instability as rated by the H&Y and UPDRS (Błaszczyk, Orawiec, Duda-Kłodowska, & Opala, 2007). Another study of 215 PD patients found that an increased sway area was an independent risk factor for recurrent falling in PD (Matinolli et al., 2007). More recently, a prospective study showed that measures of AP sway while standing on a firm and foam surface (as part of the PPA- Physiological Profile Assessment) was the *only* measure among a wide variety of demographic, clinical, and disease-specific tests that discriminated NEW fallers- fallers who fell for the first time in the 6 month study period (Kerr et al., 2010). This exciting development confirms the idea that balance-related biomechanical parameters are important in describing postural instability early in disease progression.

### *Balance Recovery*

The ability to recover balance after an unexpected perturbation is essential to preventing a fall. Studies have shown that with age and certain pathologies, strategies for balance recovery change. When presented with a balance perturbation there are two types of responses. A fixed-support response is when balance is recovered without moving the base of support. Included in this category are the ankle and hip response strategies, which involve rotating at the ankle or hip to maintain balance without moving the base of support. A change-in-support response is evoked when the perturbation is large enough that the fixed-support responses are not as effective. This usually involves changing the location and configuration of the base of support. A stepping response often requires the use of an anticipatory postural adjustment, where the body weight is shifted to the stance limb prior to liftoff of the stepping limb (Maki, McIlroy, & Fernie, 2003).

Differences in the stepping response have been widely studied in elderly subjects, who also have an increased risk of falling. Older adults tend to resort to a stepping strategy at smaller disturbances than young adults. They tend to take multiple, shorter steps, and tend to step laterally in response to an anterior

or posterior perturbation (Hall & Jensen, 2002; Luchies, Alexander, Schultz, & Ashton-Miller, 1994; McIlroy & Maki, 1996; Schulz, Ashton-Miller, & Alexander, 2005). In addition, they show larger peak ankle and hip torque and power (Madigan, 2006; Madigan & Lloyd, 2005a), reductions in hip flexion, knee flexion and extension, and ankle plantarflexion velocity (Madigan & Lloyd, 2005b). Elderly subjects with a history of falls showed smaller peak ankle torque, slower reaction time, and slower rate of ankle torque development in response to a forward lean and release perturbation (Mackey & Robinovitch, 2005), and also tended to step laterally in response to a backwards pull (Schulz et al., 2005).

Studies have investigated balance recovery in Parkinson's disease. The majority of these studies have involved subject populations with moderate to severe PD and often off medications. In fact, several studies have specifically chosen their subject population because of difficulties with balance (Chong et al., 2000; Dimitrova, Horak, & Nutt, 2004; Dimitrova, Nutt, & Horak, 2004; Horak, Dimitrova, & Nutt, 2005a; Horak, Frank, & Nutt, 1996; Horak et al., 1992b). These studies have been helpful in determining which aspects of balance are affected by PD. For instance, PD introduces abnormal foot-floor reaction forces, muscle activation patterns, and inflexibility in the feet-in-place response to surface translations (Dimitrova, Horak, et al., 2004; Dimitrova, Nutt, et al., 2004; Horak et al., 1992b), but this information does not help us understand how balance problems progress with disease progression.

The step response to a balance perturbation has also been investigated in Parkinson's disease. Jacobs *et al.* have found that moderate and severe PD subjects show differences in response compared to healthy controls. They use shorter than normal steps, use multiple anticipatory postural adjustments, have a longer step foot liftoff time, and are less consistent in the choice of stepping limb in the response to a backwards surface translation. This altered response may be due to an inability to quickly select an appropriate response since young exhibit similar behavior when they are unable to pre-select the stepping foot (Jacobs & Horak, 2006a, 2006b; King et al., 2010).

Kinematic and kinetic studies during functional tasks in persons with PD have shown significant differences in those parameters during gait, step initiation, and sit-to-stand tasks. In gait, moderately affected PD subjects on medication showed smaller ankle range of motion during the push off and swing

phases, and smaller peak plantarflexion at toe off and in the swing phase (Sofuwa et al., 2005). In gait initiation, moderate to severely affected PD subjects off medication showed decreased force production, decreased velocity, and slowed execution of anticipatory postural adjustments (Burleigh-Jacobs et al., 1997), while mild and moderate patients showed decreased COM-COP distances, indicating worse dynamic stability (Hass, Waddell, Wolf, Juncos, & Gregor, 2008). In a sit-to-stand task, moderately affected PD subjects on medication showed smaller hip flexion torque and slower time to peak torque in the ankle, knee, and hip (Mak, Levin, Mizrahi, & Hui-Chan, 2003), and reduced ability to sequence two tasks in a sit-to-walk test (Buckley, Pitsikoulis, & Hass, 2008). The differences in kinetics and kinematics during functional tasks may describe certain deficiencies that put the PD population at a higher risk of falling, but these differences during balance recovery are less understood.

It is important to note that until recently, studies in Parkinson's disease have investigated the step response only late in the disease progression when postural instability is already clinically recognized. Recently, however, it was demonstrated that even those with mild PD (H&Y II- no fall history or clinical indication of postural instability) showed impairments in the step response to a backwards pull (McVey, et al., 2009). PD participants, compared to healthy controls, took longer to liftoff for the first step, used different ankle kinematics during the step, and their center of pressure was further back at landing. Further research is needed to examine how these changes progress with a progression in disease severity.

Since interventions exist for those at increased risk of falling, and the consequences of even one fall are severe, it is important to determine the appropriate time to begin an intervention targeting fall risk, prior to the first fall event.

#### *Anticipatory Postural Adjustments:*

In order to preserve stability when taking a step, a person must shift their weight to the stance foot prior to lifting off with the swing foot for the step. It is well-established that during voluntary tasks such as gait initiation, an anticipatory postural adjustment (APA) is used in order to help propel the center of mass (COM) towards the stance foot. An APA is characterized as a vertical loading and then unloading

of the swing foot, resulting in a medial-lateral shift in the COP towards the swing leg (McIlroy & Maki, 1993). During external perturbations, these APAs are not as characteristically seen, and even when they are present they are not effective in propelling the COM towards the stance foot (McIlroy & Maki, 1993, 1999).

Investigation of the control of the center of pressure during the response to a balance disturbance has shown significant differences between those with PD compared to healthy controls, particularly in the step initiation phase. In our previous study (McVey, et al., 2009), most differences between mild PD and healthy controls occurred prior to liftoff of the first step, which implies that after liftoff the characteristics of the step were similar between the two groups. Further investigation of this phase of the response and the center of pressure showed that some of the PD patients were using multiple anticipatory postural adjustments (APAs) prior to liftoff (McVey, et al., 2008). Another recent study has shown that patients with Parkinson's disease use APAs more frequently than healthy controls (King et al., 2010), and that the use of an APA results in later liftoff times, and the use of significantly more and shorter steps to regain balance. In addition, the PD participants sometimes used multiple APAs- a much less effective response- when healthy controls never used more than one APA. This study included a large range of severity levels within the PD group, so the relationship between postural instability and PD severity level remains unclear.

In order to better understand the use of multiple APAs in PD patient, Jacobs investigated the use of APAs in healthy young subjects in response to external predictable and unpredictable perturbations (Jacobs & Horak, 2007). They defined an APA as a lateral weight shift preceding a step and measured it from the lateral displacements of the COP that occurred between onset of the disturbance to toe off of the stepping foot. In the unpredictable condition, young subjects sometimes used multiple APAs (approximately 30% of the trials showed multiple APAs compared to 70% with only one APA in the unpredictable condition). In the unpredictable condition, APA onset latencies and durations were longer. In addition, the onset latencies and durations were longest in the cases when subjects used multiple APAs.

### *Lateral Stability*

Impairments in lateral stability have been shown to be associated with aging, falls, and PD in the step response to a balance disturbance. Older adults tend to use a crossover strategy where younger adults take a side step. In addition, older adults typically take more steps and take longer and larger initial steps, (Mille, Johnson, Martinez, & Rogers, 2005). In response to forwards or backwards perturbations, older adults with a history of falling show reduced lateral stability. For instance, older adults often direct later steps of a multiple step response to a forwards or backwards disturbance more laterally than young (McIlroy & Maki, 1996).

Differences between fallers and non-fallers seem to be most prevalent in the liftoff to landing stage of the response. The initial characteristics of the step prior to liftoff are similar, but by landing fallers have moved farther sideways and with greater velocity, and the location of the step is more lateral. Older fallers also tend to have a longer step duration, earlier liftoff time, and direct their initial step more laterally compared to older non-fallers (Rogers, Hedman, Johnson, Cain, & Hanke, 2001). In addition to balance recovery, a wider step width during gait has been shown to be associated with experiencing a fall within 1 year (Maki, 1997).

Patients with Parkinson's disease have shown an increase in lateral sway during a quiet stance test (Mitchell, Collins, De Luca, Burrows, & Lipsitz, 1995), and reduced lateral stability in leaning balance tests (Menant, Latt, Menz, Fung, & Lord, 2011; van Wegen, van Emmerik, Wagenaar, & Ellis, 2001). However, the effect of both PD and PD disease severity on lateral stability during the response to a balance disturbance is not well understood.

### *Estimation of the Center of Mass*

Quantifying the motion of the center of mass is essential in quantifying lateral stability, as well as other components of balance recovery. Several methods exist to estimate the center of mass. The kinematic method involves estimating the center of mass of several body segments, and then directly

calculating the center of mass using equation  $COM = \frac{1}{M} \sum m_i * r_i$ , where  $M$  is the total mass of the body,  $m_i$  is the segment mass, and  $r_i$  is the segment center of mass (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998). Another method is based on Newton's law,  $\vec{F} = m\vec{a}$ . The position of the center of mass is approximated by double integration of the lateral ground reaction forces read from a force platform using the following equations:  $\vec{a} = \frac{\vec{F}}{m}$ ,  $\vec{v} = \int \vec{a} dt$ ,  $\vec{p} = \int \vec{v} dt$ , where  $a$  = acceleration,  $v$  = velocity,  $p$  = position,  $F$  = ground reaction forces, and  $m$  = total mass of the body (Lafond, Duarte, & Prince, 2004; Shimba, 1984; Zatsiorsky & King, 1998). The constants of integration are the initial position and initial velocity of the center of mass. These are commonly assumed to be zero, if the experimental setup can justify such an assumption. Alternatively, methods such as “zero-point-to-zero-point” integration are used to get a more accurate value for the initial velocity (Zatsiorsky & King, 1998); however this is based on the assumption that whenever the lateral ground reaction forces are zero, the COM and COP coincide, which is a good assumption in static tasks such as postural sway, but not in dynamic tasks such as balance recovery.

Numerical integration of real data can result in magnification of noise in the data and result in errors in the integration. To combat against this, often data is detrended after the first integration before integrating again (Gutierrez-Farewik, Bartonek, & Saraste, 2006; Whittle, 1997).

### *Interventions to Reduce Fall Risk*

Effective interventions exist for those at high risk of falling. In the healthy elderly population, multi-factorial programs together with targeted individual therapies are the most effective in fall prevention (Rao, 2005). These programs typically include exercise and physical therapy, gait and balance training, advice on proper use of assistive devices, review and modification of medications, treatment of postural hypotension, modification of environmental hazards, and targeted medical assessments. Individual interventions are then determined based on the factors most prevalent in the patient. These multi-factorial interventions have reduced fall risk by up to 66% (Rao, 2005).

A similar multi-factorial approach is probably necessary to reduce fall risk in persons with PD. Studies have investigated the effects of physical therapy, tai-chi, and balance and gait training on PD fallers, and while they have not been able to conclusively prevent falls, they have seen improvements in balance and gait measures (Li et al., 2012; Pohl, Rockstroh, Ruckriem, Mrass, & Mehrholz, 2003; Protas et al., 2005; Stankovic, 2004). Stankovic *et al.* studied the effect of physical therapy on balance in healthy elderly, PD fallers, and PD non-fallers (Stankovic, 2004). Physical therapy, including regular physical activity, walking with a visual stimulus, stepping, playing recreational sports, strategies for correction of motor function such as attention, maintaining an upright posture, and elongation of muscles, was applied for 30 days. Balance measures included quiet standing tasks, internal perturbation tasks, and an external perturbation. This study showed that the physical therapy program improved all of the balance measures, especially the tandem stance, single leg stance, functional reach, step, and external perturbation tests. While this study was not able to show the effect on falls, it did find an improvement in some of the measures that are used to assess fall risk.

Other studies on gait and compensatory step training in PD have shown improvements in both gait and step parameters and one study showed a 50% decrease in falls in the group that received the intervention (Jobges et al., 2004; Protas et al., 2005). Therefore, there is reason to think that targeted interventions may reduce the risk of falling in persons with PD.

### *Summary*

Parkinson's disease is a debilitating disease and postural instability leading to falls is one of the most disabling symptoms. Experiencing a fall severely impacts quality of life on physical, economic, and psychological levels. While there are effective interventions that reduce fall risk, they are often not implemented until after the first fall due to a sensitive measure of postural instability. If laboratory or clinical assessments were available to identify the appropriate time to begin targeted interventions, fall risk could be significantly reduced. Prevention of that first fall would allow persons with Parkinson's disease to maintain an independent and active lifestyle as long as possible.

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## CHAPTER THREE: THE EFFECT OF MODERATE PARKINSON'S DISEASE ON COMPENSATORY BACKWARDS STEPPING

### *Introduction*

Postural instability leading to falls is one of the most disabling symptoms of Parkinson's disease (PD). The 3 month fall rate is estimated at 46% for the general population with PD, and 21% among those who have no history of falls (Pickering et al., 2007). Falls have devastating effects on quality of life including fractures, hospitalization, loss of independence, and restriction of activities (Bloem, van Vugt, & Beckley, 2001; Gray & Hildebrand, 2000; Lachman et al., 1998; Pickering et al., 2007; Tinetti, de Leon, Doucette, Baker, & Dorothy, 1994). Interventions to reduce fall risk are most effective if they are implemented before someone falls, but the current clinical assessments for postural instability in PD are not sensitive enough to track the development of postural instability prior to a fall (Munhoz et al., 2004; Visser et al., 2003). While progress has been made in identifying clinical and physiological parameters that can more accurately predict fall risk (Duncan et al., 2012; Kerr et al., 2010; King, Priest, Salarian, Pierce, & Horak, 2012; Latt, Lord, Morris, & Fung, 2009), there is still a need to understand how postural instability progresses so that appropriate interventions can be introduced at appropriate times. Laboratory-based experiments may provide the missing link in fall-risk factor development.

The response to a balance disturbance must be quick and appropriate for the disturbance and environmental constraints that exist. The quantitative analysis of this response has many advantages over purely clinical assessments. Biomechanical parameters involving force plates, EMG, and motion tracking systems allow for complex analysis in the determination of temporal, muscular, kinematic, and kinetic parameters used to quantify the response, giving information far more detailed than possible using clinical assessments. In fact, a study has demonstrated that increased COP movement as measured by force

platforms were more associated with future falls than clinical measures of balance (Pajala et al., 2008). Another recent study demonstrated the postural sway component of a clinical balance test to be the only measure among a wide variety of clinical tests that was significantly different between a group of non-fallers with PD and a group of previous non-fallers with PD who experienced their first fall in the 6 month study period (Kerr et al., 2010). In addition, our previous study showed that biomechanical measures were able to detect differences in PD patients with no clinical indication of postural instability (McVey et al., 2009). Using multiple biomechanical parameters, such as the center of pressure movement, muscle activity, kinematics, and kinetics, may provide an even stronger assessment of postural instability.

The biomechanical analysis of the step response to a sudden balance disturbance has already shown to be effective in detecting differences between older adults who have an increased risk of falling compared to younger adults. For example, older adults use a step response at smaller disturbances, take multiple and shorter steps, and step more laterally in response to an anterior or posterior perturbation (Luchies, Alexander, Schultz, & Ashtonmiller, 1994; McIlroy & Maki, 1996; Schulz, Ashton-Miller, & Alexander, 2005). Studies in Parkinson's disease have demonstrated that participants with moderate to severe PD, compared to healthy controls, utilize shorter steps and multiple anticipatory postural adjustments (APAs) in response to a backwards surface translation (Jacobs & Horak, 2006; King, St George, Carlson-Kuhta, Nutt, & Horak, 2010). However most studies in PD have primarily focused on patients who have already been clinically diagnosed with postural instability, already exhibit major balance deficits, and have a wide range of severity levels (H&Y II-V) (Chong, Horak, & Woollacott, 2000; Dimitrova, Nutt, & Horak, 2004; Horak, Dimitrova, & Nutt, 2005; Horak, Frank, & Nutt, 1996a; Jacobs & Horak, 2006; King et al., 2010). It is not clear how postural instability progresses and how it relates to disease severity. In an attempt to elucidate potential biomechanical measurements that may be candidates for early markers of postural instability, our group recently investigated the effects of mild PD on the biomechanics of the step response (McVey et al., 2009). We demonstrated that those with mild PD (H&Y II), compared to healthy controls, took longer to liftoff for the first step, used different ankle kinematics during the step, and their center of pressure was further back at landing. The next step towards

the goal of understanding the progression of PD is to examine the effect of moderate PD on postural instability. The goal of this study was to determine if the same parameters that changed with mild PD continue to change with an increase in disease severity, so we examined the response to a balance disturbance in moderate PD.

### *Methods*

**Participants:** Ten participants diagnosed with moderate PD (PD: Age  $68 \pm 4$  years, range 61-73 years, Height:  $173 \pm 10$  cm, range 157-186 cm, Mass:  $85 \pm 19$  kg, range 56-116 kg) and ten healthy age-range matched controls (HC: Age  $68 \pm 5$  years, range 63-79 years, Height:  $175 \pm 6$  cm, range 170-186 cm, Mass:  $75 \pm 13$  kg, range 55-92 kg) completed the study (8 male and 2 female in each group). Exclusion criteria included dementia (MMSE score less than 24) (Folstein, Folstein, & McHugh, 1975), significant depression (Beck Depression Inventory  $> 14$ ) (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) and inability to ambulate without assistance. All participants gave written informed consent approved by the University of Kansas Medical Center (KUMC) Human Subject's Committee.

People diagnosed with idiopathic PD were recruited from the KUMC Parkinson's Disease and Movement Disorder Center and were assessed with the Unified Parkinson's Disease Rating Scale (UPDRS). Exclusion criteria included patients who had a H&Y score other than 3 (only participants with a H&Y score of 3 were included in this study), those who had undergone deep brain stimulation or had a history of significant musculoskeletal, neurological, or cognitive impairments other than those associated with PD were excluded. Participants with PD were instructed to maintain their normal medication schedule (Table 1) and were tested on the medication "ON" phase which was  $2.22 \pm 1.1$  hours since last dose. Healthy controls (HC) living independently were recruited from the community. Medical history and a physical examination excluded those with cardiovascular, musculoskeletal and neurological impairments.

**Task.** The participant stood with arms crossed at the chest and weight equally distributed between the feet. The participant also wore standardized footwear. For safety purposes, a safety harness connected

to an overhead support was worn by the participant and a research assistant stood nearby to help prevent injury in case of a fall. The participant wore an adjustable but rigid waist harness that was connected to a weight-drop mechanism via a cable in the back of the harness. When triggered, the weight-drop mechanism produced a posterior waist pull by dropping a weight (20% body weight) with a pull distance equal to 8.7% of waist height (Luchies, Alexander, Schultz, & Ashton-Miller, 1994). The selected pull magnitude was large enough to ensure that each participant used a step response to recover balance. The participant was instructed to respond naturally to the posterior pull, which was repeated until three good trials were obtained. Examples of bad trials included not stepping onto a force plate or obstructing the cameras' view of kinematic markers. A maximum of six trials were performed by each participant.

*Experimental Measurements:* Video, motion, force plate, electromyography (EMG), and load cell data were collected for each trial. Motion data was sampled at 100 Hz using an Optotrak (Northern Digital, Inc., Waterloo, Canada) dual bar motion analysis system. Markers were placed bilaterally on the 2<sup>nd</sup> toe, ankle, heel, calf, and knee. EMG data was measured using an eight channel Delsys surface electrode system (Delsys, Boston, MA, USA). Electrodes were placed bilaterally on the tibialis anterior (TA). Foot/floor reaction forces and moments were measured using three AMTI (Advanced Mechanical Technology Inc.; Watertown, MA, USA) six-component force plates. A biaxial custom-built load cell was used to measure the tensile force in the cable attached to the waist harness. Analog data was sampled at 1000 Hz using a 16-bit A/D data acquisition system.

*Analysis:* The parameters extracted from the balance recovery task are based on those previously determined to be significantly different between mild PD and healthy controls, making them potential candidates to be used to quantify postural instability. Strategic, temporal, kinematic, and center of pressure parameters were determined.

*Strategic Parameters:* Qualitative differences in the strategy used to recover from the balance disturbance were determined by analyzing video recorded during the trials. Parameters extracted from the video recordings include: the number of steps taken to regain balance, utilization of a single or multiple step response, and the foot used for the first step (right or left). A participant was defined as a multiple



step user if a multiple step response was used to regain balance in any of the three trials. A participant was classified as being step foot consistent if the same foot was used for the first step in all three trials. A trial was defined as a change-in-the-base-of-support if the foot lifted off the force plate and repositioned to change the base of support. The foot was required to translate 50mm or more in order to be considered a step.

*Temporal Parameters:* A threshold method was used to determine four temporal events (disturbance onset, EMG onset, and step foot liftoff and landing times) which were used to define the temporal parameters reaction time, weight shift time and step duration. The following parameters and definitions were used. 1) *Disturbance onset*: time when the cable pull force exceeded the threshold. The cable threshold was defined as the mean plus 10 standard deviations of the force signal over the initial 500 ms of data collection. 2) *Muscle onset*: the first time 25 consecutive EMG data points exceed the threshold. The EMG threshold value was defined as the mean plus five standard deviations of the signal over a 50 ms window prior to the disturbance. 3) *Reaction time*: time between disturbance onset and first TA muscle onset. 4) *Liftoff time*: time between disturbance onset and unloading of the vertical force component under the foot used for stepping, when the vertical force is less than 4% body weight. 5) *Weight shift time*: time between reaction time and liftoff time. 6) *Landing time*: time between disturbance onset and re-loading of the vertical force component under the foot used for stepping, when the vertical force is greater than 4% body weight. 7) *Step duration*: time between landing time and liftoff time.

*Ankle Kinematics:* The ankle angle was determined using the measured motion data with the kinematics portion of a 3D inverse dynamics model (Vaughan, Davis, & O'Connor, 1992). The peak ankle plantarflexion/dorsiflexion angle during the initial stage of the response (prior to liftoff) and the angle at liftoff of the first step was extracted and expressed relative to the initial configuration.

*Center of Pressure (COP) Displacement:* The anterior-posterior (AP) and medial-lateral (ML) COP locations were calculated as a function of time using the foot/floor reaction forces and moments. The whole-body COP location was analyzed from disturbance onset time to landing of the first step. The

AP and ML displacements of the COP were determined at liftoff and landing of the first step relative to the COP location at disturbance onset.

*Statistical Analysis:* Statistical analysis was performed in SPSS 20.0 (SPSS Inc., Chicago, IL). All three trials for each participant were used to evaluate group differences in strategy parameters. A  $p$ -value  $\leq 0.05$  defined significance. A Fisher's two-tailed exact test was used to determine group differences in multiple vs. single step responses and consistency in choice of stepping limb. The Wilcoxon Rank Sum test was used to evaluate group differences in the number of steps in the response.

Multiple step trials were averaged for each subject. Shapiro-Wilk's tests were used to verify the assumption of normal distribution on all parameters. If the assumption was violated, the Mann-Whitney test for independent samples was used to determine group differences. If the assumption was confirmed, independent samples t-tests were used to determine group differences between the remaining outcome parameters for each specific aim.

### *Results*

Ten people with PD and ten HC completed the study. All trials were included in the strategy analysis, but only multiple step strategy trials were included in the remaining analyses (temporal, kinematics, kinetics, COP), which left 9 participants in the PD group and 7 in the HC group. Anthropometric (weight and height), initial stance (stance width, initial COP location, initial force distribution) and pull characteristics (peak, duration, impulse) revealed no group differences and were not considered further (Table 3.2).

The backwards pull consistently resulted in a stepping response which included the use of between one and five steps without falling or external assistance required to regain balance.

*Strategy:* PD, compared to HC, utilized significantly more steps to recover from the balance disturbance (HC:  $1.66 \pm 0.63$ , PD:  $2.43 \pm 0.79$ ,  $p = .035$ ). Both PD participants and HC were more likely to use a multiple step response than a single step response (90% of PD, 70% of HC participants used a multiple step response,  $p = .496$ ). PD participants were less consistent in the foot utilized for the first step

(30% of PD, 80% of HC participants were consistent,  $p = .06$ ) but not quite to a significant level (Table 3.3).

One important observation was that in 9 trials across 6 different PD participants, compared to zero trials in HC, prior to stepping the step foot lifted off and moved slightly (Figure 3.1). This movement was not counted as the first step in the response as the change in base of support was considered negligible (foot translation less than 50mm). This movement was defined as a “base-width neutral step.” The use and characteristics of this movement will be considered as future work.

*Temporal:* The only temporal variable that showed a significant group difference was weight shift time (HC:  $242 \pm 125$  ms; PD:  $407 \pm 157$  ms;  $p = .039$ ) (Figure 3.2 and Table 3.4). Reaction time and step duration time were similar between groups.

*Kinematics:* There were no significant differences in any of the kinematic parameters considered (Table 3.5).

*Center of Pressure:* In PD, compared to HC, the COP was further back at both liftoff and landing, although not to a significant level (at liftoff, HC: 44 (36) mm, PD: 85 (44) mm posterior,  $p = .06$ ; at landing, HC: 55 (33) mm, PD: 102 (65) mm,  $p = .09$ ) (Table 6). There was no difference in COP position in the ML direction at either liftoff or landing.

### *Discussion*

The purpose of this study was to investigate whether biomechanical differences previously observed in the response to a balance disturbance in mild PD continue to persist in moderate PD. In particular, we were interested in strategy, weight shift time, ankle angle, and center of pressure position. The results of this study suggest that some of the differences persist in moderate PD, but some aspects of the response change.

*Strategy:* Moderate PD significantly affected the strategy used to respond to the balance disturbance- the PD group used more steps and tended to be less consistent in the choice of stepping foot. This is consistent with previous studies done in moderate-severe PD, but not consistent with our previous

study on mild PD. In addition, the use of the base-width neutral step was something that has not been reported before and was not seen in mild PD. The use of the base-width neutral step is very interesting, and perhaps an evolution of what we saw in mild PD. In the mild PD study, PD patients tended to shift their weight from side to side before finally lifting off, and therefore had longer weight shift times, different ankle kinematics as they fell backwards, and a further posterior COP position at landing. In moderate PD, it seems like now instead of shifting back and forth, some patients are actually *lifting off*, taking a tiny little step, before continuing their response which may be between 1-4 more steps. The inefficiency involved in taking a step that does not change the base of support as the center of mass is pulled backwards could significantly impair balance recovery.

*Temporal:* Moderate PD did not affect the reaction time or the duration of the first step. Previous studies have shown that PD does not affect the reaction time after an external perturbation (Chong, Jones, & Horak, 1999; Horak, Frank, & Nutt, 1996b; Horak, Nutt, & Nashner, 1992). In the present study, PD did increase the weight shift time, which is the time between muscle activity onset and step foot liftoff. This is consistent with what was observed in the study on mild PD, where it was suggested that the inconsistent choice of the foot used for the initial step together with the longer weight shift time in the PD, compared to the HC, may be demonstrating what Jacobs *et al.* reported when healthy subjects were unable to pre-select their stepping foot: they had several anticipatory postural adjustments, leading to longer liftoff times compared to the condition where they were allowed to choose their stepping foot (Jacobs & Horak, 2007). In this situation, it is likely the use of the base-width neutral step that is significantly contributing to longer weight shift times. In addition, it is a promising result that weight shift time is longer in both mild PD (previous study), who do not have clinically diagnosed postural instability, and moderate PD, who do have clinically diagnosed postural instability. This is an encouraging result, and perhaps an increase in weight shift time is an early indicator of postural instability in PD.

*Kinematics and COP:* Moderate PD did not affect the kinematics of the response. Notably, there was no difference in step length or height or in the ankle angle prior to liftoff. It is likely that the change in strategy to the use of the base-width-neutral step significantly changes the results seen in the ankle

angle; therefore we did not observe similar results to the study on mild PD. Moderate PD did not significantly affect the location of the COP at liftoff or landing; however PD tended to be further back at both liftoff and landing, which is consistent with the study on mild PD.

*Clinical Implications:* The results of this study are promising in the search for an early indicator of postural instability in Parkinson's disease. These results confirm that weight shift time, which is longer in mild PD (without clinical signs of postural instability), continues to be longer in moderate PD (with clinical signs of postural instability), making it a potential early marker of postural instability.

*Limitations:* Limitations of this study include the small sample size and the fact that we did not have the same number of trials for every subject (only multiple step trials included in the majority of the analysis). Another limitation of this study is that subjects were only tested *on* medication. We do not have data to describe the effects of medication on this response. However, the long-term goal of this research is to determine biomechanical tests that can be adapted for clinical use, in which case the patients would be tested on their normal medication.

### *Conclusions*

The first step in the response to a balance disturbance is impaired in moderate PD compared to healthy controls. Patients with moderate PD had to take more steps to regain balance, had a longer weight shift time, and the use of a base-width neutral step emerged as a strategy used to regain balance. Further work must examine if this is a further progression of postural instability compared to what has been observed in mild PD.

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**Table 3.1. Characteristics of PD Participants**

Sub Num	Age	Sex	UPDRS	UPDRS Motor	UPDRS #33	H&Y	Duration (yrs)	Medications	Dose/Day (mg/day)
4002	71	F	47	28	2	3	13	Carbidopa/Levodopa	600
								Carbidopa/Levodopa ER	200
								Pramipexole	1.5
4004	61	M	36	17	2	3	11	Carbidopa/Levodopa	1200
								Entacapone	1200
								Rasagiline	1
								Ropinirole PR	12
4005	69	M	57	36	2	3	3	Carbidopa/Levodopa	750
								Carbidopa/Levodopa ER	100
								Ropinirole	9
4006	71	M	47	27	2	3	7	Carbidopa/Levodopa	800
								Entacapone	800
								Rasagiline	1
								Pramipexole	3
								Amantadine	100
4007	66	M	35	23	2	3	2	Carbidopa/Levodopa	600
								Pramipexole	6
4008	63	M	65	41	2	3	9	Carbidopa/Levodopa	450
								Carbidopa/Levodopa ER	200
								Ropinirole	6
								Amantadine	200
4010	64	M	44	31	2	3	9	Carbidopa/Levodopa	400
								Carbidopa/Levodopa ER	800
								Ropinirole	6
4011	68	M	53	30	2	3	11	Carbidopa/Levodopa	1000
								Ropinirole	9
								Amantadine	200
								Benzotropine	1
4012	72	F	50	33	2	3	8	Carbidopa/Levodopa	800
								Carbidopa/Levodopa ER	700
								Pramipexole	1.5
4013	72	M	62	41	2	3	5	Carbidopa/Levodopa	400
								Amantadine	100/week
<b>Average</b>	<b>67.7</b>		<b>49.6</b>	<b>30.7</b>	<b>2</b>	<b>3</b>	<b>7.8</b>		
<b>Std Dev</b>	<b>4.00</b>		<b>10.00</b>	<b>7.56</b>	<b>0.00</b>	<b>0.00</b>	<b>3.58</b>		



**Table 3.2. Characteristics of Participant Groups; Pull and Initial Stance Characteristics**

	<b>HC (N = 10)</b>	<b>PD (N = 10)</b>	<b>p-value</b>
<b>Age (yrs)</b>	68 (5)	68 (4)	0.677
<b>Mass (kg)</b>	75 (13)	85 (19)	0.192
<b>Height (cm)</b>	175 (6)	173 (10)	0.507
<i>Pull Characteristics</i>			
<b>Peak (N)</b>	299 (57)	290 (59)	0.737
<b>Duration (ms)</b>	304 (15)	308 (34)	0.682
<b>Impulse/wh (N-s/kg-m)</b>	.251 (.04)	.232 (.06)	0.456
<i>Initial Stance Characteristics</i>			
<b>Stance Width (mm)</b>	231 (38)	248 (63)	0.455
<b>COP AP at Pull (mm)</b>	-.312 (1.9)	2.27 (5.37)	0.179
<b>COP ML at Pull (mm)</b>	.015 (1.37)	.823 (2.76)	0.418
<b>Left Vertical Force at Pull (N)</b>	394 (81)	450 (113)	0.216
<b>Right Vertical Force at Pull (N)</b>	393 (61)	431 (97)	0.241

Participant characteristics, pull characteristics, and initial stance characteristics showed no significant differences. Values are mean (standard deviation). P-values are based on t-tests.

**Table 3.3. Strategy Results**

	<b>HC (N=10)</b>	<b>PD (N=10)</b>	<b>p-value</b>
<b>No. Steps</b>	1.66 (.63)	2.43 (.79)	.035*
<b>% Consistent</b>	80%	30.0%	.064
<b>% Multiple Step</b>	70%	90%	.496

No. Steps= total number of steps in response, % Consistent= percentage of participants who stepped with the same foot in the first step of all three trials, % Multiple Step= percentage of participants who used more than 1 step to recover balance in at least one trial. \* Indicates  $p < .05$  by Wilcoxon Rank Sum Test.

**Table 3.4. Temporal Results in Multiple Step Trials**

	<b>HC (N= 7)</b>	<b>PD (N= 9)</b>	<b>p-value</b>
<b>Reaction Time (RT) (ms)</b>	138 (34)	128 (15)	.681 <sup>1</sup>
<b>Weight Shift Time (WST) (ms)</b>	242 (125)	407 (157)	.039*
<b>Step Duration (STD) (ms)</b>	149 (60)	134 (33)	.580

Significant differences observed between groups in weight shift time but not in reaction time or step duration. PD participants had longer weight shift times compared to healthy controls. <sup>1</sup>Indicates use of Mann-Whitney test instead of t-test. \*Indicates  $p < .05$  by t-test.

**Table 3.5. Kinematic Results in Multiple Step Trials**

	<b>HC (N = 7)</b>	<b>PD (N = 9)</b>	<b>p-value</b>
<b>STL (mm)</b>	183 (123)	148 (65)	0.681 <sup>1</sup>
<b>STH (mm)</b>	49.3 (34.8)	40.4 (24.9)	0.999 <sup>1</sup>
<b>Liftoff Angle (deg)</b>	-.862 (2.58)	.476 (2.27)	0.576
<b>Max Angle (deg)</b>	2.37 (1.58)	3.55 (1.86)	0.511
<b>Min Angle (deg)</b>	-1.68 (1.86)	-.993 (1.11)	0.606 <sup>1</sup>
<b>Excursion (deg)</b>	4.04 (2.24)	4.54 (1.79)	0.627

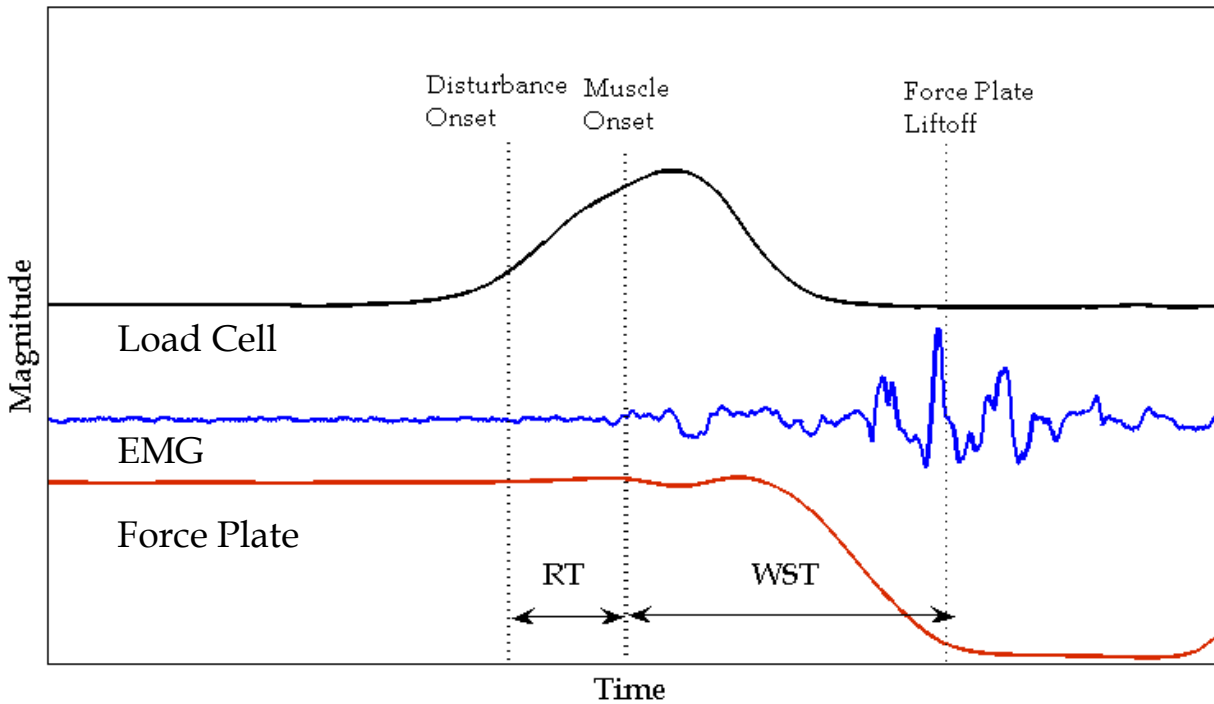
No significant differences observed in kinematic parameters. STL= step length, STH= step height, Liftoff Angle= ankle plantarflexion/dorsiflexion angle at liftoff (+ indicates plantarflexion, - indicates dorsiflexion). Max/Min Angle= max PF (max) and DF (min) prior to liftoff, Excursion= max-min ankle angle. P-values based on t-tests or Mann-Whitney tests. <sup>1</sup>Indicates use of Mann-Whitney test.

**Table 3.6. Center of Pressure Parameters**

	<b>HC (N = 7)</b>	<b>PD (N = 9)</b>	<b>p-value</b>
<b>AP COP at Liftoff (mm)</b>	-43.8 (36.3)	-85.3 (43.9)	0.063
<b>ML COP at Liftoff (mm)</b>	113 (16)	116 (43)	0.828
<b>AP COP at Landing (mm)</b>	-55.4 (33.1)	-102 (65.1)	0.088
<b>ML COP at Landing (mm)</b>	89.8 (25.6)	105 (42.2)	0.411

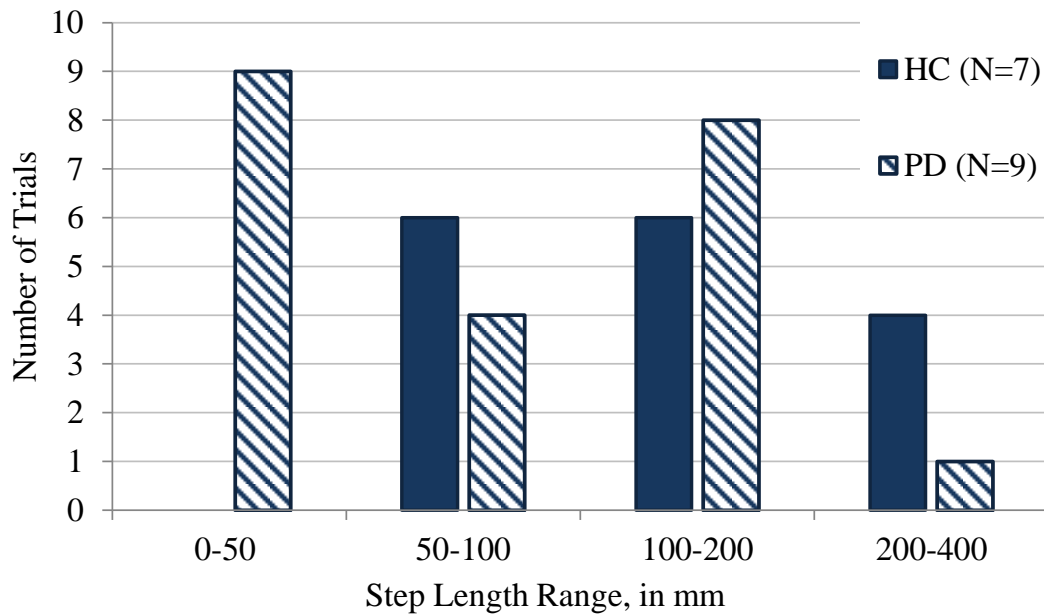
No significant differences observed between groups in center of pressure parameters. AP= anterior-posterior, ML= medial-lateral, COP= center of pressure. Liftoff and landing refer to the first step in a multiple step response. P- values based on t-tests.

**Figure 3.1. Illustration of Temporal Parameters**



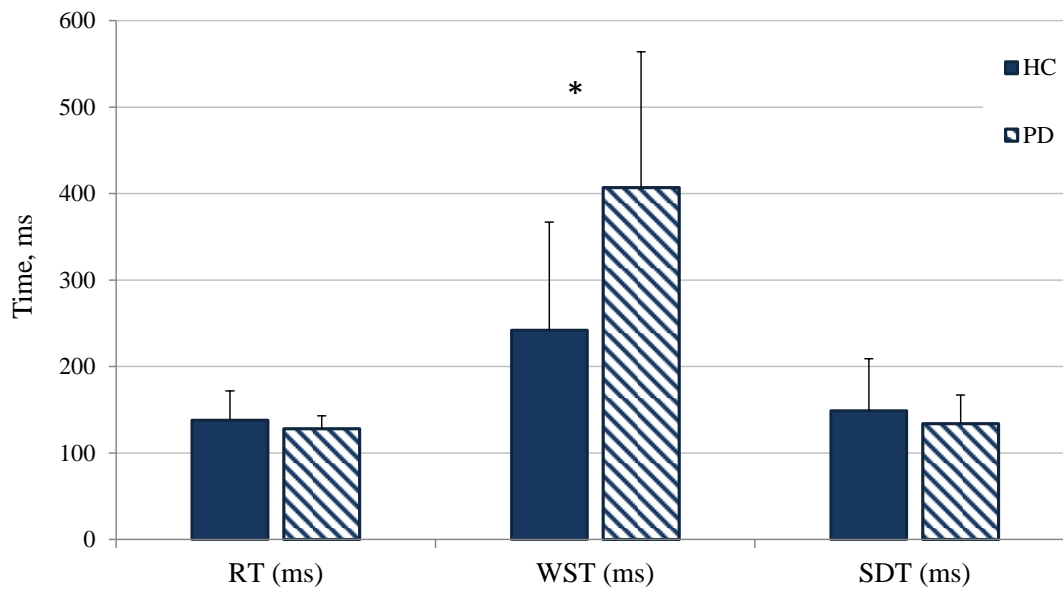
Plot illustrates the calculation of temporal parameters. RT= Reaction Time, WST= Weight Shift Time. Solid black line is load cell trace, solid blue line is EMG from stepping foot TA muscle. Solid red line is vertical force under the step foot. RT taken as time between muscle onset and disturbance onset, WST taken as time between force plate liftoff and muscle onset.

**Figure 3.2. Frequency plot of Step Length Range for Multiple Step Trials**



Frequency plot for step length: number of trials in each range of step length for the first step in multiple step responses only. Only participants in the PD group used a step smaller than 50 mm as the first step in a multiple step response.

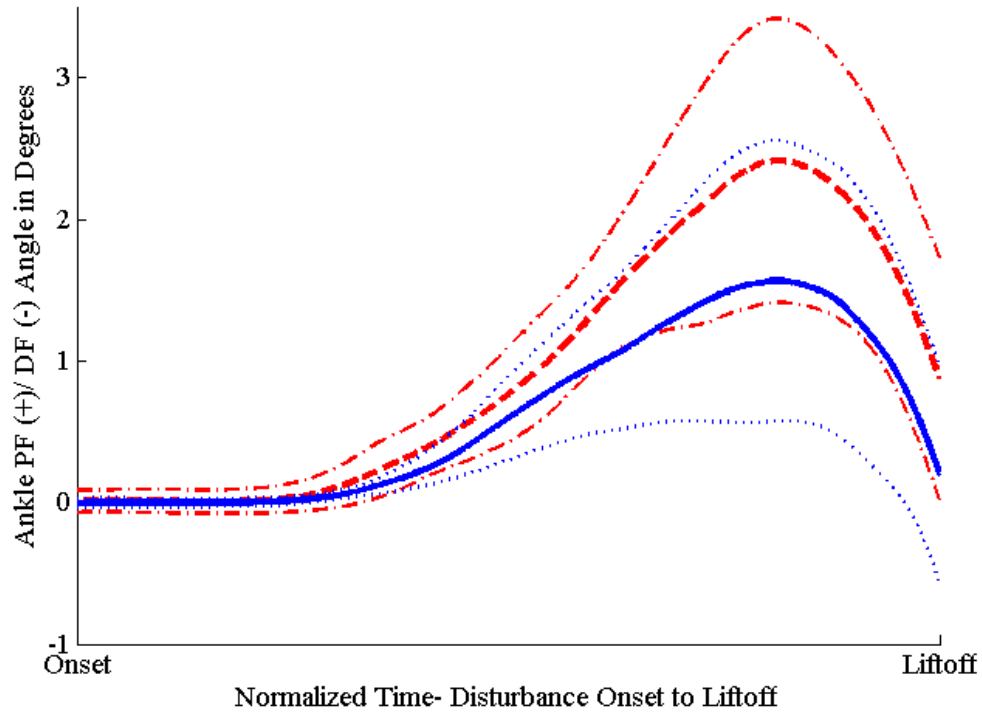
**Figure 3.3. Temporal Results in Multiple Step Trials**



Results for temporal parameters. RT= reaction time, WST= weight shift time, SDT= step duration time. Solid bars are HC group, striped bars are moderate PD group. \* indicates  $p < .05$  by t-test. PD participants had significantly longer WST compared to HC.

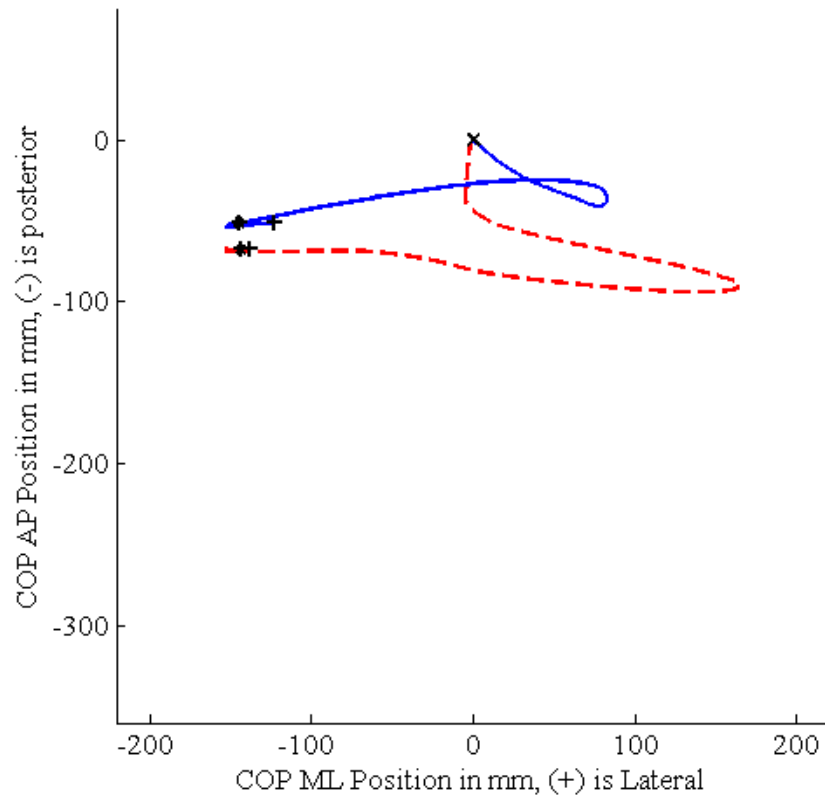


**Figure 3.4. Group Average Ankle Angle**



Group Average Ankle Angle: Solid Blue Line= mean ankle angle for HC group. Dashed red line= mean ankle angle for PD group. Mean lines for first step in multiple step responses only. Dashed blue lines=  $\pm 1$  standard deviation of the HC mean, dash-dotted red lines=  $\pm 1$  standard deviation of the PD mean. No significant difference in ankle angle prior to liftoff.

**Figure 3.5. Representative Center of Pressure Plot**



Representative plots of COP from disturbance onset to landing of the first step in a HC (solid blue line) and PD (dashed red line) participant. X marks disturbance onset, \* marks liftoff, and + marks landing. Plot illustrates significantly different COP movement in PD compared to HC during first step in the response.

## CHAPTER FOUR: THE EFFECT OF MODERATE PARKINSON'S DISEASE ON THE PREPARATION FOR COMPENSATORY BACKWARD STEPPING

### *Introduction*

Postural instability leading to falls is one of the most disabling symptoms of Parkinson's disease (PD). The 3 month fall rate is estimated at 46% for the general population with PD, and 21% among those who have no history of falls (Pickering et al., 2007). Falls have devastating effects on quality of life including fractures, hospitalization, loss of independence, and restriction of activities (Bloem, van Vugt, & Beckley, 2001; Gray & Hildebrand, 2000; Lachman et al., 1998; Pickering et al., 2007; Tinetti, de Leon, Doucette, Baker, & Dorothy, 1994). Interventions to reduce fall risk are most effective if they are implemented before someone falls, but the current clinical assessments for postural instability in PD are not sensitive enough to track the development of postural instability prior to a fall (Munhoz et al., 2004; Visser et al., 2003). While progress has been made in identifying clinical and physiological parameters that can more accurately predict fall risk (Duncan et al., 2012; Kerr et al., 2010; King, Priest, Salarian, Pierce, & Horak, 2012; Latt, Lord, Morris, & Fung, 2009), there is still a need to understand how postural instability progresses so that appropriate interventions can be introduced at appropriate times. Laboratory-based experiments may provide the missing link in fall-risk factor development.

The response to a large balance perturbation often involves a step response to reconfigure the base of support, which must be done quickly and appropriately in order to prevent a fall. PD impairs the step response and subjects typically use shorter than normal steps, multiple anticipatory postural adjustments, have a longer liftoff time, and are less consistent in the choice of stepping limb (Jacobs & Horak, 2006; Jacobs, Horak, & Nutt, 2005). It is thought that this altered response may result from an

inability to quickly select an appropriate response, as similar effects occur when young adults are unable to pre-select their stepping foot (Jacobs & Horak, 2007).

In order to preserve stability when taking a step, a person must shift their weight to the stance foot prior to lifting off with the swing foot for the step. It is well-established that during voluntary tasks such as gait initiation, an anticipatory postural adjustment (APA) is used in order to help propel the center of mass (COM) towards the stance foot. An APA is characterized as a vertical loading and then unloading of the swing foot, resulting in a medial-lateral shift in the COP towards the swing leg (McIlroy & Maki, 1993). During external perturbations, these APAs are not as characteristically seen, and even when they are present they are not effective in propelling the COM towards the stance foot (McIlroy & Maki, 1993, 1999).

Investigation of the control of the center of pressure during the response to a balance disturbance has shown significant differences between those with PD compared to healthy controls, particularly in the step initiation phase. In our previous study (McVey, et al., 2009), most differences between mild PD and healthy controls occurred prior to liftoff of the first step, which implies that after liftoff the characteristics of the step were similar between the two groups. Further investigation of this phase of the response and the center of pressure showed that some of the PD patients were using multiple anticipatory postural adjustments (APAs) prior to liftoff (McVey, et al., 2008). Another recent study has shown that patients with Parkinson's disease use APAs more frequently than healthy controls (King, St George, Carlson-Kuhta, Nutt, & Horak, 2010), and that the use of an APA results in later liftoff times, and the use of significantly more and shorter steps to regain balance. In addition, the PD participants sometimes used multiple APAs, a less efficient response, compared to healthy controls who never used more than one APA. However, this study included a large range of severity levels within the PD group, so the relationship between postural instability and PD severity level remains unclear.

In order to better understand the use of multiple APAs in PD patients, Jacobs investigated the use of APAs in healthy young subjects in response to external predictable and unpredictable perturbations (Jacobs & Horak, 2007). They defined an APA as a lateral weight shift preceding a step and measured it

from the lateral displacements of the COP that occurred between onset of the disturbance to toe off of the stepping foot. In the unpredictable condition, young subjects sometimes used multiple APAs (approximately 30% of the trials showed multiple APAs compared to 70% with only one APA). In addition, APA onset latencies and durations were longer in the unpredictable condition compared to the predictable condition. Finally, the onset latencies and durations were longest in the cases when subjects used multiple APAs.

Previous studies of postural instability in PD have primarily focused on patients who already exhibit balance deficits (Chong, Horak, & Woollacott, 2000; Dimitrova, Nutt, & Horak, 2004; Horak, Dimitrova, & Nutt, 2005; Horak, Frank, & Nutt, 1996; Jacobs & Horak, 2006). For instance, Jacobs *et al.* demonstrated that moderate and severe PD participants, compared to healthy controls, utilized shorter steps (Jacobs & Horak, 2006), multiple anticipatory postural adjustments, and were less consistent in the choice of stepping limb in response to a backwards surface translation (Jacobs *et al.*, 2005). A preliminary study by our group has demonstrated impairments in balance recovery in patients with early Parkinson's disease and no clinical signs of postural instability (H&Y = 2). This study demonstrated that those with PD but without postural instability, compared to age-range-matched controls, used a longer weight shift time (time between muscle onset and liftoff of the stepping foot), altered ankle rotation prior to liftoff, and had a more posterior displacement of the COP at landing of the first step in the response. The most interesting result of the preliminary study was that most of the differences between the two groups were found in the first stage of the response- prior to liftoff of the first step. In addition, the COP patterns observed during this stage were quite different between the two groups.

Therefore, the goal of this study was to further investigate the COP movement during the preparation stage of the step response in PD patients with clinically diagnosed postural instability (H&Y 3), compared to healthy controls. Further studies are required to determine if these variables are sensitive and specific to postural instability.

## *Methods*

**Participants:** Ten participants diagnosed with moderate PD (PD: Age  $68 \pm 4$  years, range 61-73 years, Height:  $173 \pm 10$  cm, range 157-186 cm, Mass:  $85 \pm 19$  kg, range 56-116 kg) and ten healthy age-range matched controls (HC: Age  $68 \pm 5$  years, range 63-79 years, Height:  $175 \pm 6$  cm, range 170-186 cm, Mass:  $75 \pm 13$  kg, range 55-92 kg) completed the study (8 male and 2 female in each group). Exclusion criteria included dementia (MMSE score less than 24) (Folstein, Folstein, & McHugh, 1975), significant depression (Beck Depression Inventory  $> 14$ ) (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) and inability to ambulate without assistance. All participants gave written informed consent approved by the University of Kansas Medical Center (KUMC) Human Subject's Committee.

People diagnosed with idiopathic PD were recruited from the KUMC Parkinson's Disease and Movement Disorder Center and were assessed with the Unified Parkinson's Disease Rating Scale (UPDRS). Exclusion criteria included patients who had a H&Y score other than 3 (only participants with H&Y 3 were included in this study), those who had undergone deep brain stimulation or had a history of significant musculoskeletal, neurological, or cognitive impairments other than those associated with PD. Participants with PD were instructed to maintain their normal medication schedule (Table 4.1) and were tested on the medication "ON" phase which was  $2.22 \pm 1.1$  hours since last dose. Healthy controls (HC) living independently were recruited from the community. Medical history and a physical examination excluded those with cardiovascular, musculoskeletal and neurological impairments. Characteristics of PD participants are shown in Table 4.1.

**Task.** The participant stood with arms crossed at the chest and weight equally distributed between the feet. The participant also wore standardized footwear. For safety purposes, a safety harness connected to an overhead support was worn by the participant and a research assistant stood nearby to help prevent injury in case of a fall. The participant wore an adjustable but rigid waist harness that was connected to a weight-drop mechanism via a cable in the back of the harness. When triggered, the weight-drop mechanism produced a posterior waist pull by dropping a weight (20% body weight) with a pull distance

equal to 8.7% of waist height (Luchies, Alexander, Schultz, & Ashton-Miller, 1994). The selected pull magnitude was large enough to ensure that each participant used a step response to recover balance. The participant was instructed to respond naturally to the posterior pull, which was repeated until three good trials were obtained. Examples of bad trials included not stepping onto a force plate or obstructing the cameras' view of kinematic markers. A maximum of six trials were performed by each participant.

*Experimental Measurements:* Video, motion, force plate, electromyography (EMG), and load cell data were collected for each trial. Motion data was sampled at 100 Hz using an Optotrak (Northern Digital, Inc., Waterloo, Canada) dual bar motion analysis system. Markers were placed bilaterally on the 2<sup>nd</sup> toe, ankle, heel, calf, and knee. EMG data was measured using an eight channel Delsys surface electrode system (Delsys, Boston, MA, USA). Electrodes were placed bilaterally on the tibialis anterior (TA). Foot/floor reaction forces and moments were measured using three AMTI (Advanced Mechanical Technology Inc.; Watertown, MA, USA) six-component force plates. A biaxial custom-built load cell was used to measure the tensile force in the cable attached to the waist harness. Analog data was sampled at 1000 Hz using a 16-bit A/D data acquisition system.

*Analysis:* Force plate and load cell data were filtered using a second order low pass Butterworth filter with a cutoff frequency of 20 Hz. Initial and final-time artifacts were minimized using forward and backward reflection of the data (Smith, 1989), and phase shift was eliminated by using forward and backward passes (Winter, 1990). Data from all trials were processed using MATLAB (Mathworks, Natick, MA, USA). Trials were classified as single or multiple step trials. Only the first step in a multiple step response was compared. A step was defined if the foot lifted off the force plate and repositioned to change the base of support. The foot was required to translate 50 mm or more in order to be considered a step. One important observation was that in 9 trials across 6 different PD participants, compared to zero trials in HC, prior to stepping the step foot was unloaded and slightly translated. This movement was not counted as the first step in the response as the change in base of support was considered negligible (foot translation less than 50 mm). This movement was defined as a “base-width neutral step.” The use and characteristics of this movement will be considered as future work.

The whole body center of pressure (COP) was calculated for the time period of disturbance onset to liftoff of the first step, and divided into two stages. Stage one was defined as disturbance onset to weight shift onset. Stage two was defined as weight shift onset to step foot liftoff. Weight shift onset was defined as the last change in the location of the COP in the ML direction prior to liftoff. The anterior-posterior (AP) and medial-lateral (ML) displacement, path length, average velocity, and time duration of each stage were calculated.

*Center of Pressure Parameters:* The anterior-posterior (AP) and medial-lateral (ML) displacement, path length, average velocity, and the duration of each stage were calculated. Displacement was calculated as the difference between starting and ending positions of the COP in each stage. Path length was defined as the total distance traveled by the COP in each stage. Average velocity over the stage was calculated as distance/time in each stage.

*Anticipatory Postural Adjustments:* Anticipatory postural adjustments were defined similarly to the methods in Jacobs and McIlroy. APAs were determined by looking at the lateral COP signal from 500 ms prior to onset of the disturbance to liftoff of the first step. The baseline signal was defined by the average of the signal for 500 ms prior to onset of the disturbance. If the COP traveled more than 1cm from the baseline an APA was noted to begin. Trials were classified as having 0, 1, or 2 or more APAs. Figures 4.1 and 4.2 illustrate the different preparation strategies.

*Statistical Analysis:* Statistical analysis was done with SPSS 20.0 (SPSS Inc., Chicago, IL). A  $p$ -value  $\leq 0.05$  was used for significance. The Fisher's Exact Test was used to evaluate group differences in the number of trials where multiple APAs were used and consistency of preparation strategy. Shapiro-Wilks tests were used to test COP parameters for normal distribution. Those that were normally distributed were analyzed using the Student's T-Test, those that were not normally distributed were analyzed using the Mann-Whitney U Test.

In order to further examine the effect of the use of multiple APAs on the response, follow up tests were done to compare stepping strategy (0 or 1 APAs compared to 2 or more APAs) to the COP parameters. Linear mixed modeling, with subject as a random factor, and a variance components



covariance structure were used. Differences were analyzed among three groups: healthy controls (who all used either 0 or 1 APAs), PD who used 0 or 1 APAs, and PD who used 2 or more APAs.

### *Results*

Ten people with PD and ten HC completed the study. All trials were included in the strategy analysis, but only multiple step strategy trials were included in the remaining analyses (temporal, kinematics, kinetics, COP), which left 9 participants in the PD group and 7 in the HC group. Anthropometric (weight and height), initial stance (stance width, initial COP location, initial force distribution) and pull characteristics (peak, duration, impulse) revealed no group differences and were not considered further (Table 4.2).

The backwards pull consistently resulted in a stepping response which included the use of between one and five steps without falling or external assistance required to regain balance.

*Strategy:* PD, compared to HC, utilized significantly more steps to recover from the balance disturbance (HC:  $1.66 \pm 0.63$ , PD:  $2.43 \pm 0.79$ ,  $p = .035$ ). Both PD participants and HC were more likely to use a multiple step response (90% PD, 70% HC participants,  $p = .496$ ).

*APAs:* Figure 4.3 shows the proportion of trials for each preparation strategy. PD participants used multiple APAs in 37% (11/30) of all trials, compared to HC who never used multiple APAs ( $p=.0003$ ). Approximately 55% (6/11) of the trials where multiple APAs were used involved the use of a base-width neutral step. The preparation strategy (use of 0, 1, or 2 or more APAs) was more variable in PD participants, with only 30% (3/10) using a consistent strategy compared to 80% (8/10) of HC participants (not significant in Fisher's Exact Test:  $p=.07$ ).

In multiple step trials, PD participants used multiple APAs in 41% of multiple step trials, where HC never used more than one APA ( $p=.005$ ). Figure 4.4 shows the proportion of trials in each group using 0, 1, or 2 or more APAs. Approximately half (5/9, 56%) of the trials where multiple APAs were used were trials that involved the use of a base-width neutral step. The preparation strategy (use of 0, 1, or

2 or more APAs) was more variable in PD participants, with only 30% (3/10) using a consistent strategy compared to 80% (8/10) of HC participants.

*Center of Pressure Parameters:* There were significant differences in several COP parameters, all in the first stage of the response, that is prior to the final weight shift began for the first step. In stage 1, PD compared to HC, demonstrated a longer AP COP Path Length (PD:  $85.2 \pm 48.6$  mm, HC:  $33.7 \pm 22.4$  mm,  $p = .02$ ), a longer ML COP Path Length (PD:  $135.1 \pm 85.1$  mm, HC:  $30.3 \pm 29.5$  mm,  $p = .008$ ), a longer duration of stage 1 (PD:  $384.3 \pm 173.8$  ms HC:  $231.6 \pm 65.6$  ms,  $p = .034$ ), and a higher ML average velocity during stage 1 (PD:  $286 \pm 132$  mm/s, HC:  $108 \pm 100$  mm/s,  $p = .01$ ) (Table 4.3 and Figure 4.5,4.6). There were no significant differences in any parameters in stage 2 of the response (Table 4.4).

*Effects of Preparation Strategy on COP Characteristics:* Follow up tests further examined variables where significant differences were found to determine the effect of preparation strategy on the COP parameters. Significant differences were found in the duration of stage 1, ML and AP path length, and ML average velocity in stage 1 between the PD group using multiple APAs and both the healthy controls and the PD group using 0 or 1 APAs (Table 4.5 and Figure 4.7).

*Clinical Scores not significantly related to Preparation Strategy:* None of the clinical UPDRS measures investigated (total UPDRS score, UPDRS motor score, and UPDRS PIGD sub-section) were significantly different between PD participants who used multiple APAs compared to PD participants who never used multiple APAs. There was a trend towards higher scores across all measures, but not to a significant level (Figure 4.8). In addition, we saw no correlation between fall history and the use of multiple APAs. In fact, only two of the participants did not report a history of falls, and both of these participants used multiple APAs in at least one trial.

## *Discussion*

The goal of this study was to investigate the COP during the preparation stage of the step response in PD patients with clinically diagnosed postural instability (H&Y 3), compared to healthy

controls. Participants with moderate PD used different preparation strategies prior to taking a step, and the movement of the center of pressure during the preparation stage reflected these differences.

Participants with moderate PD used more than one APA prior to liftoff of the first step in a multiple step response in 37% of trials. The use of multiple APAs in the PD group is consistent with findings by King *et al.*, who found that 14% of patients with mild-severe PD used multiple APAs, and healthy controls never used multiple APAs (King *et al.*, 2010). The increased percentage of multiple APA trials in this study can possibly be explained by the use of the base-width neutral step. If we ignore trials in which a base-width neutral step occurs, the use of multiple APAs reduces to 13.3% (4/30), which is consistent with King *et al.* In addition, the current study compared healthy controls to only those with moderate PD (H&Y 3) where the King *et al.* study included a more diverse patient population with mild to severe PD (H&Y 1.5-4 on medication).

McIlroy and Maki have shown that healthy subjects generally do not use an APA in response to an unpredictable disturbance, and that when they do use an APA, it is generally not effective in propelling the COM towards the stance foot (McIlroy & Maki, 1993). They concluded that the APA may represent a pre-planned response that is interrupted by the need to react quickly to the destabilization caused by the perturbation. It is unclear why the PD participants not only persist in using APAs, but often use more than 1 APA. Horak *et al.* found that healthy young participants were likely to use more than 1 APA in response to an unexpected perturbation when they were not allowed to pre-select their stepping foot, again suggesting that multiple APAs suggest an interruption to a pre-planned response (Jacobs & Horak, 2007).

No significant correlations were found with respect to clinical scores and preparation strategy. This may be due in part to the homogeneous nature of the PD participants, as all were H&Y 3. The analysis of additional PD severity levels to this study may help to understand how clinical scores relate to preparation strategy. In addition, part of the motivation for this study is the lack of sensitivity of clinical measures, so it is not surprising that the clinical scores are not picking up on these changes within this group. The fact that we found no correlation with fall history is disappointing, as that would be a sure

indicator that these analyses may be useful in the development of a more sensitive fall-risk predictor, but this study was not designed to study fall risk, and further studies need to more carefully examine the potential correlation of fall risk to preparation strategy.

*Clinical Implications:* The results of this study are promising in the search for an early indicator of postural instability in Parkinson's disease. These results suggest that COP measures during the preparation phase of the response may be early indicators of postural instability. This is exciting because the preparation phase of the response cannot be visually observed, so the use of these measures may offer clinical insight that is not otherwise available.

The center of pressure parameters further explain the differences we observed in the first study, which showed that moderate PD patients had longer weight shift time and altered COP patterns prior to liftoff of the response. The results from this study suggest that the main impairment in the response happens prior to the final weight shift, and the measures of path length, time to final weight shift, and ML average velocity may be important measures of postural instability.

### *Limitations*

A limitation of this study is that subjects were only tested *on* medication. We do not have data to describe the effects of medication on this response. However, the long-term goal of this research is to determine biomechanical tests that can be adapted for clinical use, in which case the patients would be tested on their normal medication.

Another limitation of this study is the small sample size, particularly when groups were further divided based on preparation strategy. It is noted that the linear mixed model analyses are exploratory, and care has been taken to be conservative in interpretation of all results.

### *Conclusions*

The preparation phase of the response to an external perturbation is impaired in moderate PD. The use of multiple APAs results in later liftoff times and significantly different movement in the center

of pressure prior to liftoff. Furthermore, the differences in the response can be attributed to the stage of preparation prior to final weight shift. This portion of the response and these parameters should be further investigated for their value in a more sensitive measure of postural instability.

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**Table 4.1. Characteristics of PD Participants**

Sub Num	Age	Sex	UPDRS	UPDRS Motor	UPDRS #33	H&Y	Duration (yrs)	Medications	Dose/Day (mg/day)
4002	71	F	47	28	2	3	13	Carbidopa/Levodopa	600
								Carbidopa/Levodopa ER	200
								Pramipexole	1.5
4004	61	M	36	17	2	3	11	Carbidopa/Levodopa	1200
								Entacapone	1200
								Rasagiline	1
								Ropinirole PR	12
4005	69	M	57	36	2	3	3	Carbidopa/Levodopa	750
								Carbidopa/Levodopa ER	100
								Ropinirole	9
4006	71	M	47	27	2	3	7	Carbidopa/Levodopa	800
								Entacapone	800
								Rasagiline	1
								Pramipexole	3
								Amantadine	100
4007	66	M	35	23	2	3	2	Carbidopa/Levodopa	600
								Pramipexole	6
4008	63	M	65	41	2	3	9	Carbidopa/Levodopa	450
								Carbidopa/Levodopa ER	200
								Ropinirole	6
								Amantadine	200
4010	64	M	44	31	2	3	9	Carbidopa/Levodopa	400
								Carbidopa/Levodopa ER	800
								Ropinirole	6
4011	68	M	53	30	2	3	11	Carbidopa/Levodopa	1000
								Ropinirole	9
								Amantadine	200
								Benzotropine	1
4012	72	F	50	33	2	3	8	Carbidopa/Levodopa	800
								Carbidopa/Levodopa ER	700
								Pramipexole	1.5
4013	72	M	62	41	2	3	5	Carbidopa/Levodopa	400
								Amantadine	100/week
<b>Average</b>	<b>67.7</b>		<b>49.6</b>	<b>30.7</b>	<b>2</b>	<b>3</b>	<b>7.8</b>		
<b>Std Dev</b>	<b>4.00</b>		<b>10.00</b>	<b>7.56</b>	<b>0.00</b>	<b>0.00</b>	<b>3.58</b>		

**Table 4.2. Characteristics of Participant Groups; Initial Stance and Pull Characteristics**

	<b>HC (N = 10)</b>	<b>PD (N = 10)</b>	<b>p-value</b>
<b>Age (yrs)</b>	68 (5)	68 (4)	0.677
<b>Mass (kg)</b>	75 (13)	85 (19)	0.192
<b>Height (cm)</b>	175 (6)	173 (10)	0.507
<i>Pull Characteristics</i>			
<b>Peak (N)</b>	299 (57)	290 (59)	0.737
<b>Duration (ms)</b>	304 (15)	308 (34)	0.682
<b>Impulse/wh (N-s/kg-m)</b>	.251 (.04)	.232 (.06)	0.456
<i>Initial Stance Characteristics</i>			
<b>Stance Width (mm)</b>	231 (38)	248 (63)	0.455
<b>COP AP at Pull (mm)</b>	-.312 (1.9)	2.27 (5.37)	0.179
<b>COP ML at Pull (mm)</b>	.015 (1.37)	.823 (2.76)	0.418
<b>Left Vertical Force at Pull (N)</b>	394 (81)	450 (113)	0.216
<b>Right Vertical Force at Pull (N)</b>	393 (61)	431 (97)	0.241

Participant characteristics, pull characteristics, and initial stance characteristics showed no significant differences. Values are mean (standard deviation). P-values are based on t-tests.



**Figure 4.1. Illustration of Preparation Strategies in Healthy Controls**

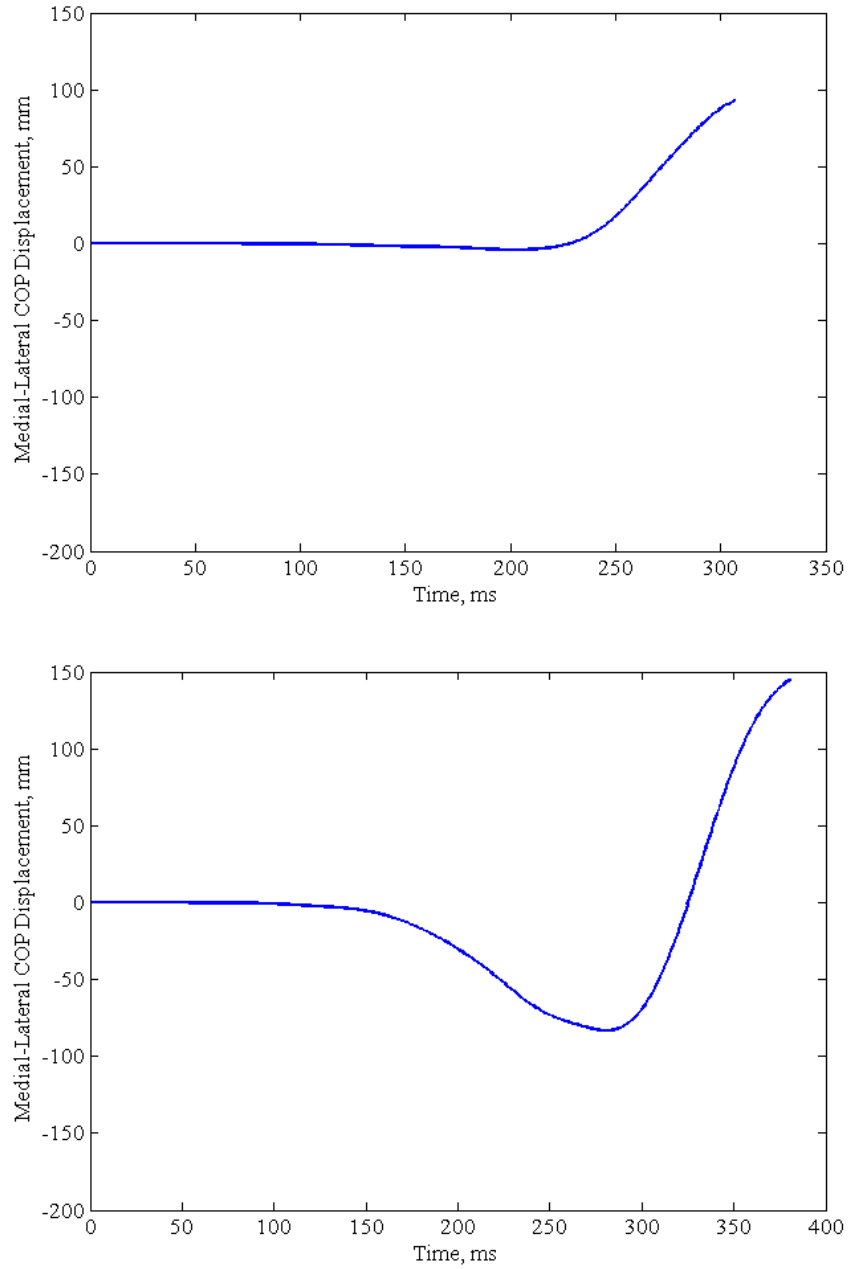


Illustration of Preparation Strategies in Healthy Controls. Top graph is a trial where no APA was used; bottom graph is a trial where one APA was used. Plots begin at disturbance onset and end at liftoff of the first step. Positive numbers are towards stance foot, negative numbers towards swing foot. Notice in the bottom graph (1 APA) the COP shifts to the swing foot first before shifting to stance foot.

**Figure 4.2. Illustration of Preparation Strategies in PD Participants**

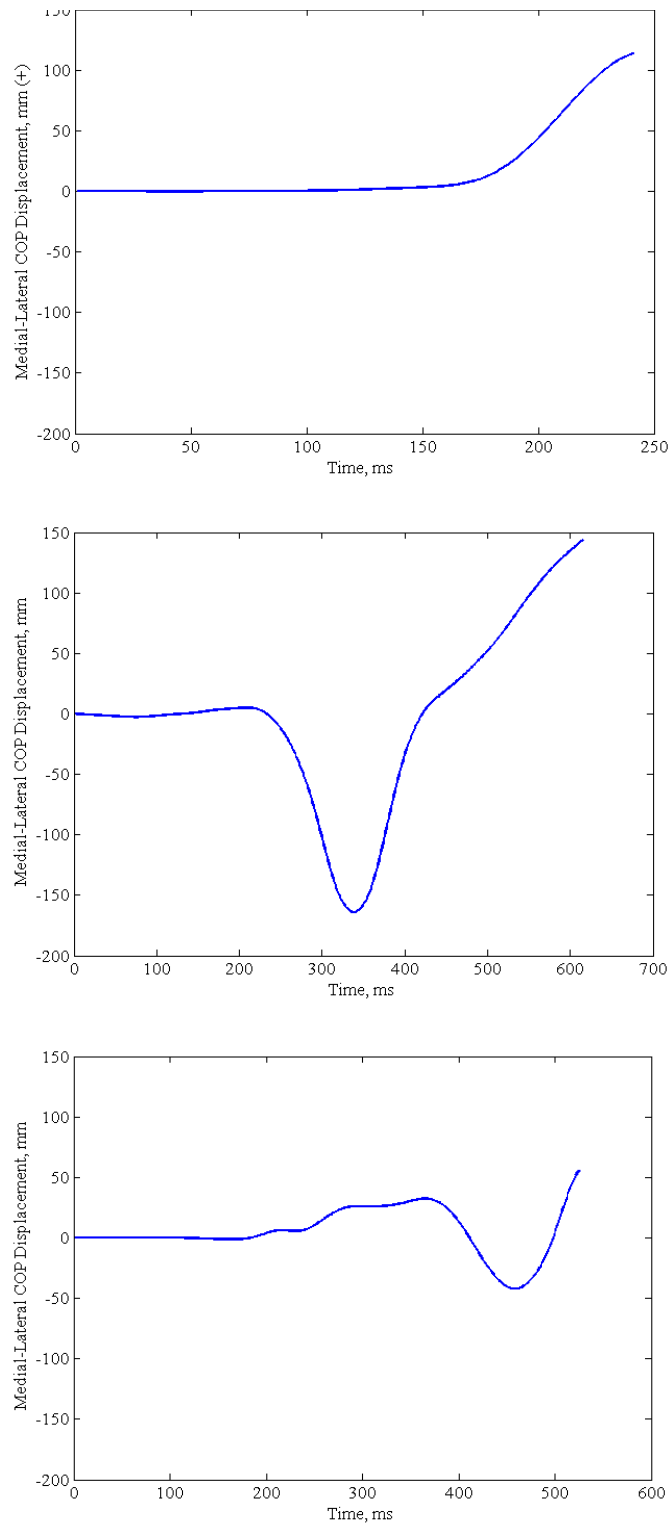
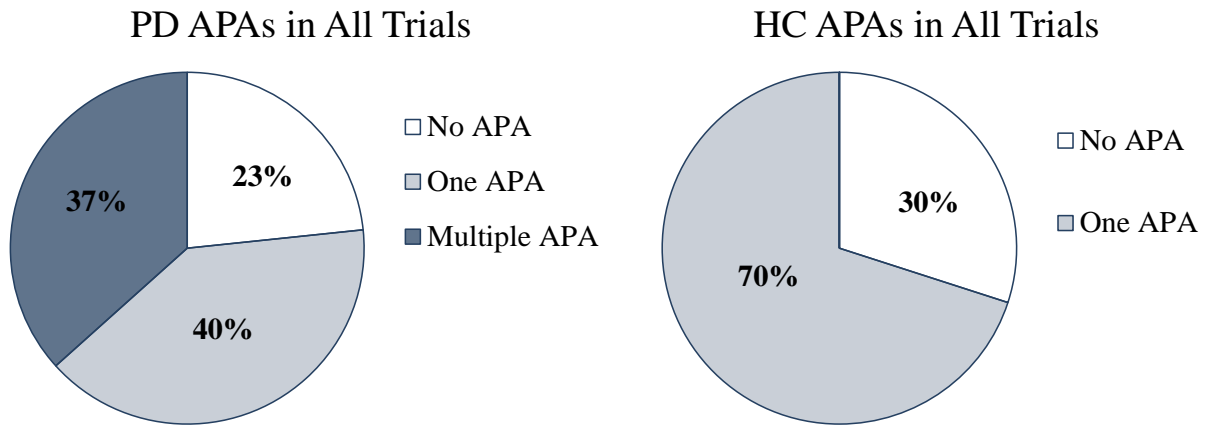


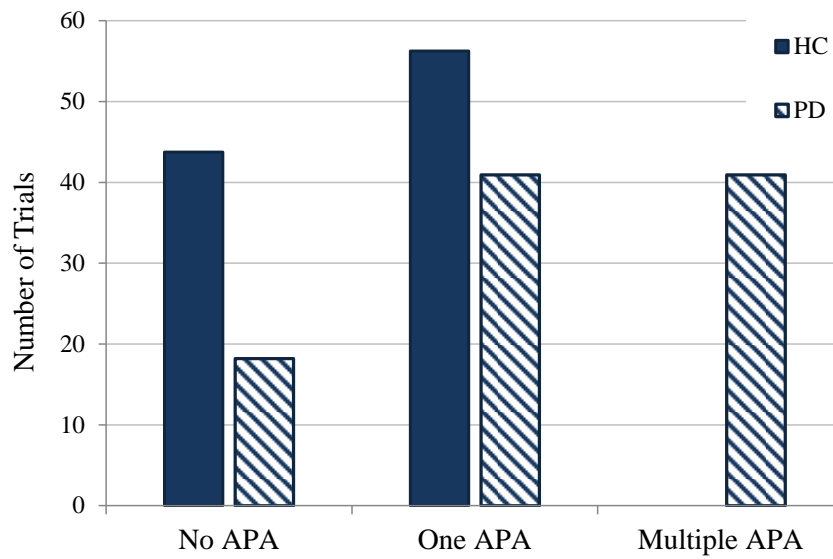
Illustration of Preparation Strategies in PD Participants. Top graph is a trial where no APA was used; middle graph is a trial where one APA was used, bottom graph is a trial where two APAs were used. Plots begin at disturbance onset and end at liftoff of the first step. Positive numbers are towards stance foot, negative numbers towards swing foot. Notice in the bottom graph (2 APAs) the COP shifts directions more than once prior to shifting towards stance foot.

**Figure 4.3. Frequency of Preparation Strategy Across Groups**



Frequency of Preparation Strategy Across Groups. APA= Anticipatory Postural Adjustment, PD= Moderate Parkinson's Disease Group, HC= Healthy Control Group. PD participants used multiple APAs in 37% of trials, compared to HC participants who never used multiple APAs.

**Figure 4.4. Preparation Strategies in Multiple Step Trials**



Preparation Strategies in Multiple Step Trials. APA= Anticipatory Postural Adjustment, PD= Moderate Parkinson's Disease Group, HC= Healthy Control Group. Healthy controls always used 0 or 1 APA, where PD participants occasionally used multiple APAs.

**Figure 4.5. Center of Pressure Parameters in Stage 1 of Response**

Multiple Steps- Stage 1	HC (N=7)	PD (N=9)	p-value
<b>AP Displacement Stage 1 (mm)</b>	-26.2 (25.8)	-66.0 (46.8)	0.063
<b>ML Displacement Stage 1 (mm)</b>	26.5 (29.3)	52.7 (71.8)	0.382
<b>AP Path Length Stage 1 (mm)</b>	33.7 (22.4)	85.2 (48.6)	0.022*
<b>ML Path Length Stage 1 (mm)</b>	30.3 (29.5)	135.1 (85.1)	0.008*
<b>Time Stage 1 (ms)</b>	231.6 (65.6)	384.3 (173.8)	0.034*
<b>AP Ave. Vel. Stage 1 (mm/ms)</b>	.127 (.066)	.181 (.087)	0.197
<b>ML Ave. Vel. Stage 1 (mm/ms)</b>	.108 (.100)	.286 (.132)	0.01*

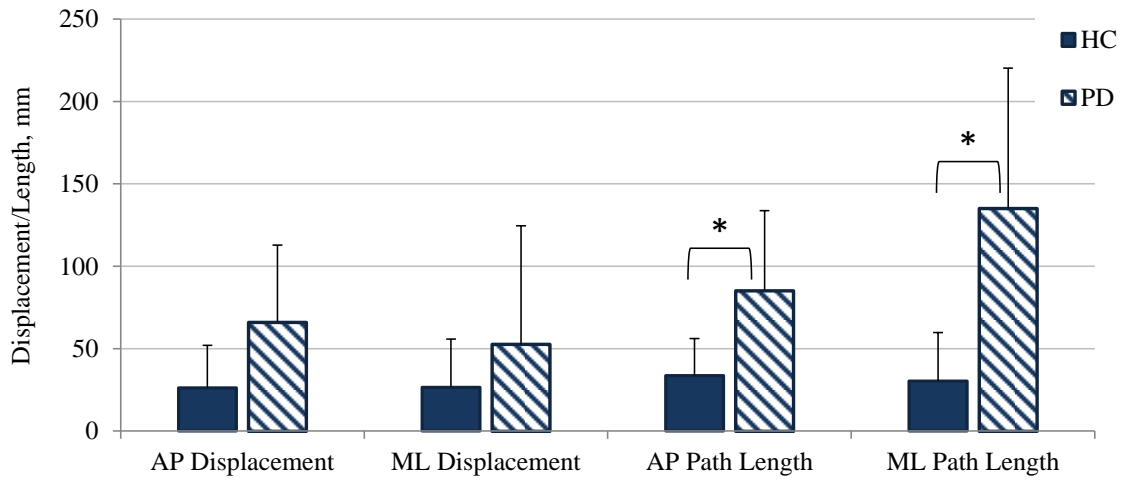
Center of Pressure Parameters in Stage 1 of the response (prior to final weight shift), in the first step of multiple step responses. AP= anterior-posterior, ML= medial-lateral, HC= healthy control, PD= moderate PD group. P-values based on t-tests, \* indicates  $p < .05$ .

**Figure 4.6. Center of Pressure Parameters in Stage 2 of Response**

Multiple Steps- Stage 2	HC (N=7)	PD (N=9)	p-value
<b>AP Position at Liftoff (mm)</b>	-43.8 (36.3)	-85.3 (43.9)	0.063
<b>ML Position at Liftoff (mm)</b>	-112.6 (16.3)	-116.1 (42.9)	0.828
<b>AP Displacement Stage 2 (mm)</b>	-17.5 (21.7)	-19.3 (28.2)	0.889
<b>ML Displacement Stage 2 (mm)</b>	-138.4 (34.5)	-168.2 (104.2)	0.482
<b>AP Path Length Stage 2 (mm)</b>	33.8 (12. 1)	36.7 (18.9)	0.735
<b>ML Path Length Stage 2 (mm)</b>	139.5 (35.0)	171.7 (104.8)	0.451
<b>Time Stage 2 (ms)</b>	149.1 (58.4)	151.5 (62.4)	0.939
<b>AP Ave. Vel. Stage 2 (mm/ms)</b>	.266 (.125)	.308 (.189)	0.625
<b>ML Ave. Vel. Stage 2 (mm/ms)</b>	1.066 (.536)	1.140 (.673)	0.816

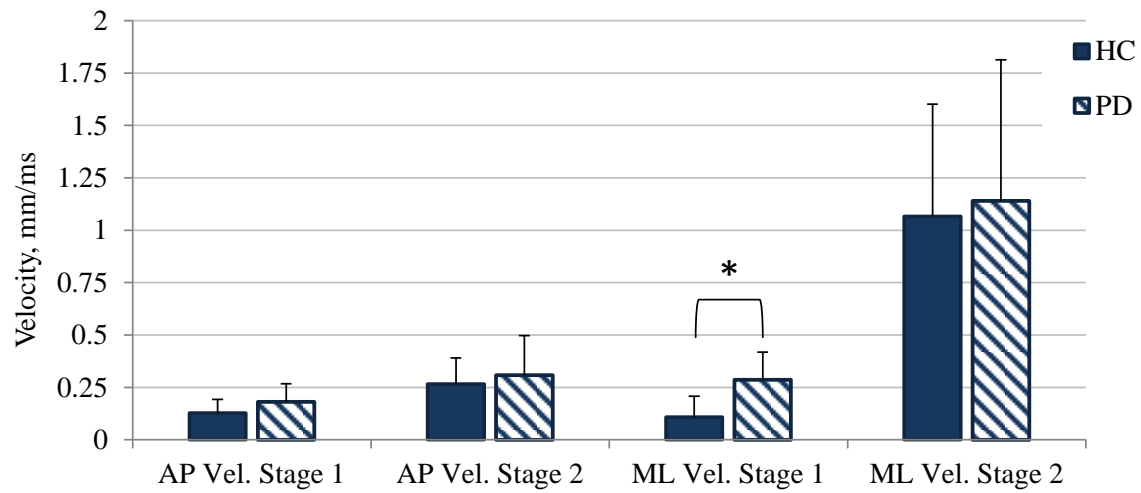
Center of Pressure Parameters in Stage 2 of the response (final weight shift to liftoff of first step) in the first step of multiple step responses. AP= anterior-posterior, ML= medial-lateral, HC= healthy control, PD= moderate PD group. P-values based on t-tests.

**Figure 4.7. Center of Pressure Parameters in Stage 1 of Response**



Center of Pressure Parameters in Stage 1 of the response (prior to final weight shift), in the first step of multiple step responses. AP= anterior-posterior, ML= medial-lateral, HC= healthy control, PD= moderate PD group. P-values based on t-tests, \* indicates  $p < .05$ .

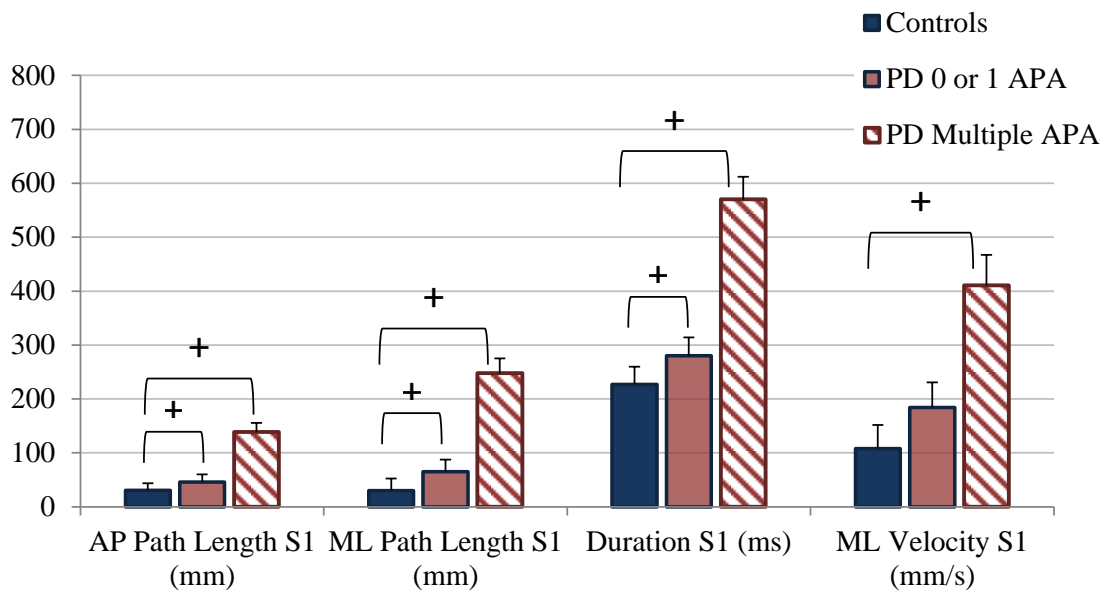
**Figure 4.8. Average Velocities During Preparation Phase of Response**



Average velocities during Stage 1 and Stage 2 of first step in response. Stage 1= Disturbance onset to final weight shift, Stage 2= final weight shift to liftoff of first step, \* Indicates  $p < .05$  by t-test.



**Figure 4.9. COP Parameters by Preparation Strategy**



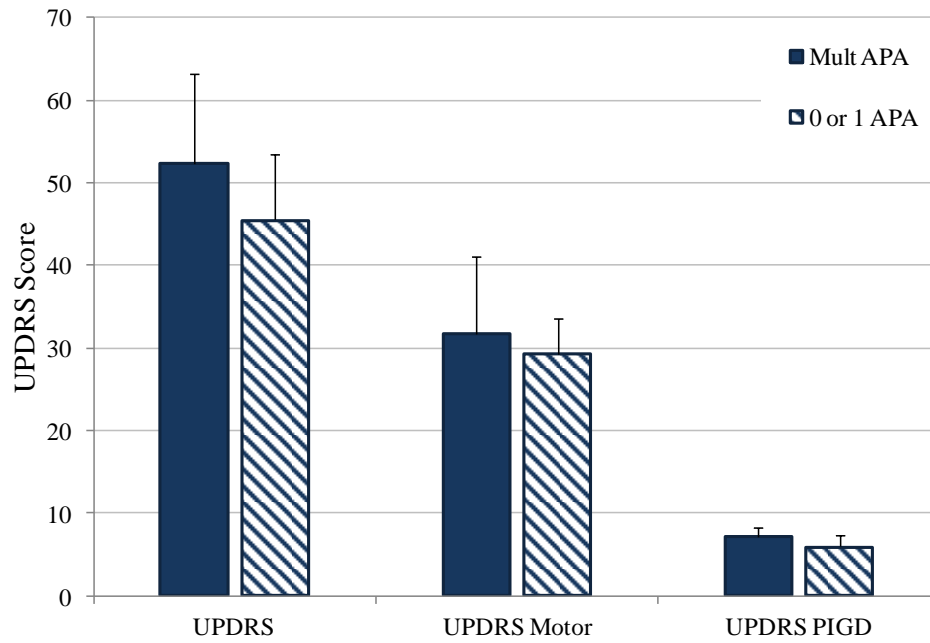
COP parameters by preparation strategy (controls (N=7) who all used either 0 or 1 APAs, PD who used either 0 or 1 APA (N=8), and PD who used 2 or more APAs (N=6)). + Indicates pairwise group difference from Linear Mixed Model after Bonferroni correction with  $p < .05$ .

**Table 4.3. COP Parameters by Preparation Strategy**

	<b>HC</b> (N = 7)	<b>PD 0 or 1 APA</b> (N = 8)	<b>PD Multiple APAs</b> (N = 6)	<b>Main P</b>
<b>AP Path Length S1 (mm)</b>	30.5 (13.3)	45.7 (14.6)	138 (18)	0.001
<b>ML Path Length S1 (mm)</b>	29.9 (22.3)	64.8 (23.0)	247 (28)	0.000
<b>Duration S1 (ms)</b>	227 (33)	280 (34)	570 (42)	0.000
<b>ML Velocity S1 (mm/s)</b>	108 (44)	184 (47)	410 (57)	0.002

COP Parameters by Preparation Strategy. AP= anterior-posterior, ML= medial-lateral, S1= stage 1 (onset of disturbance to final weight shift prior to liftoff). APA= anticipatory postural adjustment. Main P= p-value for effect of strategy based on Linear Mixed Model.

**Figure 4.10. UPDRS Scores by Preparation Strategy**



UPDRS scores by preparation strategy. APA= anticipatory postural adjustment, UPDRS= Unified Parkinson's Disease Rating Scale, PIGD= Postural instability and Gait Disorder subsection of UPDRS.

## CHAPTER FIVE: THE EFFECT OF STEP STRATEGY ON BALANCE RECOVERY IN MODERATE PARKINSON'S DISEASE

### *Introduction*

Postural instability leading to falls is one of the most disabling symptoms of Parkinson's disease (PD). The 3 month fall rate is estimated at 46% for the general population with PD, and 21% among those who have no history of falls (Pickering et al., 2007). Falls have devastating effects on quality of life including fractures, hospitalization, loss of independence, and restriction of activities (Bloem, van Vugt, & Beckley, 2001; Gray & Hildebrand, 2000; Lachman et al., 1998; Pickering et al., 2007; Tinetti, de Leon, Doucette, Baker, & Dorothy, 1994). Interventions to reduce fall risk are most effective if they are implemented before someone falls, but the current clinical assessments for postural instability in PD are not sensitive enough to track the development of postural instability prior to a fall (Munhoz et al., 2004; Visser et al., 2003). While progress has been made in identifying clinical and physiological parameters that can more accurately predict fall risk (Duncan et al., 2012; Kerr et al., 2010; King, Priest, Salarian, Pierce, & Horak, 2012; Latt, Lord, Morris, & Fung, 2009), there is still a need to understand how postural instability progresses so that appropriate interventions can be introduced at appropriate times. Laboratory-based experiments may provide the missing link in fall-risk factor development.

The response to a large balance perturbation often involves a step response to reconfigure the base of support, which must be done quickly and appropriately in order to prevent a fall. It is well documented that this response deteriorates with age, and even further with Parkinson's disease. Older adults use smaller, multiple steps to respond to a balance disturbance where young adults use a single larger step (Luchies, Alexander, Schultz, & Ashtonmiller, 1994; Maki & McIlroy, 2005; McIlroy & Maki, 1996). PD further impairs the step response and subjects typically use shorter than normal steps,

multiple anticipatory postural adjustments, have a longer step foot liftoff time, and are less consistent in the choice of stepping limb compared to healthy age-matched controls (Jacobs & Horak, 2006; Jacobs, Horak, & Nutt, 2005).

Studies in Parkinson's disease have demonstrated that participants with moderate to severe PD, compared to healthy controls, utilize shorter steps and multiple anticipatory postural adjustments (APAs) in response to a backwards surface translations (Jacobs & Horak, 2006; King, St George, Carlson-Kuhta, Nutt, & Horak, 2010). However most studies in PD have primarily focused on patients who have already been clinically diagnosed with postural instability, already exhibit major balance deficits, and have a wide range of severity levels (H&Y II-V) (Chong, Horak, & Woollacott, 2000; Dimitrova, Nutt, & Horak, 2004; Horak, Dimitrova, & Nutt, 2005; Horak, Frank, & Nutt, 1996; Jacobs & Horak, 2006; King et al., 2010). It is not clear how postural instability progresses and how it relates to disease severity. In an attempt to elucidate potential biomechanical measurements that may be candidates for early markers of postural instability, our group recently investigated the effects of mild PD on the biomechanics of the step response and determined that even mild PD impairs the step response (McVey, et al., 2009). Subsequent work showed that the first step in the response to a balance disturbance is also impaired in moderate PD compared to healthy controls. Patients with moderate PD had to take more steps to regain balance, had a longer weight shift time, and the use of a base-width neutral step emerged as a strategy used to regain balance. The purpose of this study was to examine the effect of response strategy on balance recovery and to characterize the base-width neutral step (BNS).

### *Methods*

**Participants:** Ten participants diagnosed with moderate PD (PD: Age  $68 \pm 4$  years, range 61-73 years, Height:  $173 \pm 10$  cm, range 157-186 cm, Mass:  $85 \pm 19$  kg, range 56-116 kg) and ten healthy age-range matched controls (HC: Age  $68 \pm 5$  years, range 63-79 years, Height:  $175 \pm 6$  cm, range 170-186 cm, Mass:  $75 \pm 13$  kg, range 55-92 kg) completed the study (8 male and 2 female in each group).

Exclusion criteria included dementia (MMSE score less than 24) (Folstein, Folstein, & McHugh, 1975),

significant depression (Beck Depression Inventory > 14) (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) and inability to ambulate without assistance. All participants gave written informed consent approved by the University of Kansas Medical Center (KUMC) Human Subject's Committee.

People diagnosed with idiopathic PD were recruited from the KUMC Parkinson's Disease and Movement Disorder Center and were assessed with the Unified Parkinson's Disease Rating Scale (UPDRS). Exclusion criteria included patients who had a H&Y other than 3 (only H&Y 3 included in this study), those who had undergone deep brain stimulation or have had a history of significant musculoskeletal, neurological, or cognitive impairments other than those associated with PD. Participants with PD were instructed to maintain their normal medication schedule (Table 5.1) and were tested on the medication "ON" phase which was  $2.22 \pm 1.1$  hours since last dose. Healthy controls (HC) living independently were recruited from the community and age-range matched to the PD group. Medical history and a physical examination excluded those with cardiovascular, musculoskeletal and neurological impairments.

*Task:* The participant stood with arms crossed at the chest and weight equally distributed between the feet. The participant also wore standardized footwear. For safety purposes, a safety harness connected to overhead support was worn by the participant and a research assistant stood nearby to help prevent injury in case of a fall. The participant wore an adjustable but rigid waist harness that was connected to a weight-drop mechanism via a cable in the back of the harness. When triggered, the weight-drop mechanism produced a posterior waist pull by dropping a weight (20% body weight) with a pull distance equal to 8.7% of waist height (Luchies, Alexander, Schultz, & Ashton-Miller, 1994). The selected pull magnitude was large enough to ensure that each participant used a step response to recover balance. The participant was instructed to respond naturally to the posterior pull, which was repeated until three good trials were obtained. Examples of bad trials included not stepping onto a force plate or obstructing the cameras' view of kinematic markers. A maximum of six trials were performed by each participant.

*Experimental Measurements:* Video, motion, force plate, electromyography (EMG), and load cell data were collected for each trial. Motion data was sampled at 100 Hz using an Optotrak (Northern

Digital, Inc., Waterloo, Canada) dual bar motion analysis system. Markers were placed bilaterally on the 2<sup>nd</sup> toe, ankle, heel, calf, and knee. EMG data was measured using an eight channel Delsys surface electrode system (Delsys, Boston, MA, USA). Electrodes were placed bilaterally on the tibialis anterior (TA). Foot/floor reaction forces and moments were measured using three AMTI (Advanced Mechanical Technology Inc.; Watertown, MA, USA) six-component force plates. A biaxial custom-built load cell was used to measure the tensile force in the cable attached to the waist harness. Analog data was sampled at 1000 Hz using a 16-bit A/D data acquisition system.

*Analysis:* Force plate and load cell data were filtered using a second order low pass Butterworth filter with a cutoff frequency of 20 Hz. Initial and final-time artifacts were minimized using forward and backward reflection of the data (Smith, 1989), and phase shift was eliminated by using forward and backward passes (Winter, 1990). Data from all trials were processed using MATLAB (Mathworks, Natick, MA, USA). Trials were classified as single or multiple step trials. A step was defined if the foot lifted off the force plate and repositioned to change the base of support. A step less than 50 mm in length was defined as a base-width neutral step.

The purpose of this study was to understand and quantify the use of the base-width neutral step as a strategy for balance recovery, and to understand the effects of this strategy on balance recovery.

The *number of steps* used in the response was determined by visual inspection of the video recording of the trial. A threshold method was used to determine step foot liftoff and landing times. *Step duration* was defined as the time between liftoff and landing. *Step length* was defined as the distance between the location of the heel marker at liftoff and landing. *Step height* was defined as the maximum vertical position of the heel marker between liftoff and landing.

Time to balance recovery was determined by 1) estimating the position of the center of mass, and 2) determining when balance recovery occurred. The position of the center of mass was approximated by double integration of the lateral ground reaction forces (Gutierrez-Farewik, Bartonek, & Saraste, 2006; Lafond, Duarte, & Prince, 2004; Whittle, 1997). The constants of integration were the initial position (assumed to be in the same position as the COP at the instant of disturbance onset) and initial speed of the

center of mass (assumed to be zero). To reduce error, COM speed data was detrended before integrating the second time (Gutierrez-Farewik et al., 2006; Whittle, 1997). Balance recovery was defined as the time that the direction of the COM movement changed from backwards to forwards. *Time to balance recovery* was defined as the time between balance recovery and disturbance onset. The *center of mass position at balance recovery* was defined as the AP position of the COM at balance recovery. Figures 5.8 and 5.9 depict the AP COM trajectory and time of balance recovery for all strategy types.

Three strategy categories were defined: single step (SS): recovered balance by taking only one step, multiple step (MS): recovered balance by taking 2 or more steps, and the base-width neutral step (BNS): recovered balance by taking 2 or more steps, the first of which was a very small (less than 50mm) step. The step characteristics (step length, height, and duration) and balance recovery parameters (time to balance recovery and AP COM position at balance recovery) were compared for each group.

*Statistical Analysis:* In order to determine the effect of strategy (single step, multiple step, or use of a base-width neutral step), step characteristics and recovery parameters were compared across the three different categories in each group using a linear mixed model with subject as a random factor and a variance components covariance structure. Post-hoc tests between groups were done and a Bonferonni correction for multiple comparisons was applied for each set of comparisons.

The first groups to be compared were HC vs. PD, with all stepping strategies grouped together (N=10 in each group). Shapiro-Wilk's tests were used to verify the assumption of normal distribution on all parameters. If the assumption was violated, the Mann-Whitney test for independent samples was used to determine group differences. If the assumption was confirmed, independent samples t-tests were used to determine group differences between the remaining outcome parameters for each specific aim.

Next, single and multiple step trials were separated into either a single or multiple step categories within the PD and HC groups and the resulting 4 groups were compared using the linear mixed model (HC single step (N=7), HC multiple step (N=7), PD single step (N=4), PD multiple step (N=9)). Note that each subject could have a trial in more than one category. Finally, the PD multiple step group was further divided into a category of subjects with a BNS as the first step, and the five groups were compared (HC



single steps (N=7), HC multiple steps (N=7), PD single steps (N=5), PD multiple steps (N=8), and PD BNS (N=6)).

### *Results*

Ten people with PD and ten HC completed the study. Anthropometric (age, weight and height), initial stance (stance width, initial COP location, initial force distribution) and pull characteristics (peak, duration, impulse) revealed no group differences and were not considered further (Table 5.2).

All participants regained balance by taking at least one step, and were not necessarily consistent in strategy type over the three trials. The breakdown of subjects with at least one trial in a strategy category was as follows: single steps: 7 HC and 5 PD, multiple steps: 7 HC and 8 PD, BNS steps: 0 HC, 6 PD. One PD participant used a BNS step in each of the three trials, and one PD participant used a single step response in each of the three trials.

*Effects of Moderate PD on Step Characteristics:* Participants with moderate PD used a significantly shorter first step in terms of length, height, and duration as shown in Figure 5.1 (Step Length: PD:  $96.7 \pm 55.2$  mm, HC:  $222.0 \pm 139.8$  mm,  $p=.000$ , Step Height: PD:  $28.3 \pm 21.4$  mm, HC:  $59.0 \pm 38.3$  mm,  $p=.002$ , Step Duration: PD:  $111.4 \pm 36.3$  ms, HC:  $176.0 \pm 62.9$ ,  $p=.000$ ).

*Effects of Multiple Step Strategy on Step Characteristics:* Results in the following two sections are presented as estimated group means  $\pm$  standard error, as calculated in the linear mixed model. There was a significant main effect for group on all step parameters (Step Length:  $p=.001$ , Step Height:  $p=.008$ , Step Duration:  $p=.001$ ). Step characteristics for each group are presented in Figure 5.2. Pairwise tests revealed group differences between the single step responses in the HC group compared to other response groups. For instance, single step responses in the healthy control group were significantly longer in length than any other group (HC SS:  $274.8 \pm 33.6$  mm; HC MS:  $185.7 \pm 31.4$  mm,  $p=.018$ ; PD SS:  $123.5 \pm 34.8$  mm,  $p=.024$ ; PD MS:  $87.0 \pm 28.7$  mm,  $p=.002$ ). Single step responses in the healthy control group were also significantly larger in both height ( $p=.008$ ) and duration ( $p=.001$ ) compared to the first step in the multiple step responses in the PD group. Finally, single step responses in the healthy control group were

also shorter in duration compared to the PD single step group ( $p = .034$ ). In addition, a trend towards smaller, shorter steps in the PD multiple step group compared to the HC multiple step group was present, but was not significant after the Bonferroni correction. The single step responses in the PD group were not significantly larger or longer than the first step in a multiple step response within the PD group.

*Effects of a Base-width Neutral Step as the First Step in the Response:* The use of a base-width neutral step (BNS) was defined if the first step in the response was less than 50mm in length. This strategy was observed in 9 trials across 6 PD participants, and never observed in the control group. Characteristics of this BNS are shown compared to other step strategies in Figure 5.3. There was a significant main effect for group on all step parameters (Step Length:  $p = .000$ , Step Height:  $p = .002$ , Step Duration:  $p = .000$ ). Pairwise tests revealed several group differences in the base-width neutral step compared to the other step strategies. For instance, the base-width neutral steps were significantly smaller in both length and height, and shorter in duration compared to the HC SS group (Step Length: PD BNS:  $41.6 \pm 32.0$  mm, HC SS:  $273.9 \pm 32.4$  mm,  $p = .000$ ; Step Height: PD BNS:  $10.1 \pm 10.3$ , HC SS:  $73.0 \pm 10.1$ ,  $p = .000$ ; Step Duration: PD BNS:  $77.0 \pm 16.1$  ms, HC SS:  $194.1 \pm 14.9$  ms,  $p = .000$ ). BNS steps were also significantly shorter in length and duration compared to HC MS (Step Length: PD BNS:  $41.6 \pm 32.0$  mm, HC MS:  $186.4 \pm 30.4$ ,  $p = .03$ , Step Duration:  $77.0 \pm 16.1$  ms, HC MS:  $160.1 \pm 14.4$ ,  $p = .01$ ). Finally, BNS steps were significantly shorter in duration compared to PD MS (PD BNS:  $77.0 \pm 16.1$  ms, PD MS:  $122.9 \pm 14.4$ ,  $p = .03$ ). Several other trends existed in step parameters between strategy categories, but they did not reach significance after the Bonferroni correction.

Further investigation of the use of the BNS showed that 3/6 of the participants who used a base-width neutral step used it on the first of the three trials. Two of those participants did not use a BNS again, while one of those participants used it on all three trials. In addition, 5/6 of the participants who used a base-width neutral step used the less-affected side to take the base-width neutral step, while only one participant took the BNS with the more affected side.

*Effects of Moderate PD on Balance Recovery Parameters:* Participants with moderate PD, compared to HC, used significantly more steps to regain balance (PD:  $2.73 \pm 1.33$ , HC:  $1.67 \pm 0.71$ ,  $p =$

.001) and had significantly longer time to balance recovery than HC (PD:  $1639 \pm 475$  ms, HC:  $1347 \pm 283$  ms,  $p = .006$ ) but the center of mass was not significantly further posterior at the time of balance recovery (PD:  $382 \pm 312$  mm, HC:  $317 \pm 128$  mm,  $p = .767$ ), as shown in Figure 5.4.

*Effects of Multiple Step Strategy on Balance Recovery Parameters:* Results in the following two sections are presented as estimated group means  $\pm$  standard error, as calculated in the linear mixed model. There was a significant main effect for group on recovery time ( $p = .000$ ), but not for the AP position of COM at recovery ( $p = .142$ ). Pairwise tests revealed a significant difference between the PD MS group compared to all other groups in recovery time as shown in Figure 5.5 (PD MS:  $1794 \pm 74.6$  ms, PD SS:  $1214 \pm 124$  ms,  $p = .000$ ; HC MS:  $1312 \pm 87.5$  ms,  $p = .000$ ; HC SS:  $1387 \pm 93.5$  ms,  $p = .008$ ). The position of the center of mass at recovery time trended towards being further back in the PD MS group compared to all other groups, but this result did not reach significance after the Bonferroni correction.

*Effects of a Base-width Neutral Step as the First Step in the Response:* There was a significant main effect for group on recovery time ( $p = .000$ ), but not for AP COM position ( $p = .09$ ). Pairwise tests revealed a significant difference between the PD BNS group compared to the PD SS group, HC MS group, and HC SS group in recovery time as shown in Figure 5.6 (PD BNS:  $1993 \pm 112$  ms, PD SS:  $1214 \pm 119$  ms,  $p = .000$ ; HC MS:  $1312 \pm 84.3$  ms,  $p = .000$ ; HC SS:  $1387 \pm 90.1$  ms,  $p = .000$ ). In addition, recovery time was significantly longer in the PD MS group compared to the PD SS group (PD MS:  $1656 \pm 93.5$  ms, PD SS:  $1214 \pm 119$  ms,  $p = .05$ ). The position of the center of mass at recovery time was furthest back in the PD BNS group, but this result did not reach significance after the Bonferroni correction.

*Clinical Scores not significantly related to Strategy Type:* None of the clinical UPDRS measures investigated (total UPDRS score, UPDRS motor score, and UPDRS PIGD sub-section) were significantly different between PD participants who never used a BNS compared to PD participants who used a BNS in at least one trial. There was a trend towards higher total UPDRS and UPDRS motor scores, but not to a significant level (Figure 5.7). In addition, we saw no correlation between fall history and the use of a

BNS. In fact, only two of the participants reported no history of falls (i.e. non fallers), and both of these participants used a BNS response in one trial.

### *Discussion*

The purpose of this study was to examine the effect of response strategy on balance recovery and to characterize the base-width neutral step (BNS). Maki *et al.* reported the use of a BNS in response to lateral perturbations, but did not quantify the characteristics or frequency of use of this step in older adults compared to young adults (Maki, Edmondstone, & McIlroy, 2000).

*Effects of PD and strategy on step characteristics:* In general, the single stepping strategy in the HC group had longer step lengths, duration, and height than the other stepping strategies in either group. Step length for single steps in the HC group was longer than any other stepping strategy in either group. This is consistent with previous findings of small step length in PD during compensatory stepping (Burleigh-Jacobs, Horak, Nutt, & Obeso, 1997; Jacobs & Horak, 2006; Maki & McIlroy, 2005). The base-width neutral step was, by definition, shorter in length than other stepping strategies. It was also shorter in duration compared to all other strategies in both groups, and shorter in height compared to the HC SS group.

*Effects of PD and Step Strategy on Balance Recovery:* Patients with PD took significantly longer to recover balance. When the groups were separated into SS and MS strategy groups, it appears that this increase is primarily attributed to the multiple step responses, as the PD MS strategy category took significantly longer to recover balance compared to every other category. Subdividing the groups once more to separate the PD BNS strategy category, we see that some, but not all, of this difference can be attributed to the use of the BNS as a first step in the response, as this group took significantly longer to recover compared to every group except the PD MS group. Interestingly, no significant differences were found in the AP position of the COM at recovery time, although it trended towards being further back in the PD MS and PD BNS categories compared to both HC categories and the PD SS category.

Finally, the PD SS group recovered balance the fastest and with the least backwards movement of their COM, likely due to the smaller step used compared to the HC groups. If a single step strategy, even considering the smaller step, is the most efficient at recovering balance, that may provide one potential target of step training and physical therapy in PD.

*Use of BNS as a strategy for balance recovery in PD?* Several questions arise regarding the use of the BNS as a first step in the response. Previous studies have shown that PD patients were more likely to use an anticipatory postural adjustment (APA), and even sometimes used multiple APAs in preparation for a compensatory step, resulting in longer liftoff times and the use of significantly more and shorter steps to regain balance (King et al., 2010); McVey, et al. (2008), where healthy controls never used multiple APAs. One question for further exploration is whether the use of this BNS is an evolution of the multiple APA phenomenon, that is, are participants who may have used multiple APAs earlier in the disease progression now using a BNS instead? At what cost and what benefit? From this study, it appears that the cost of using a BNS is a longer time to balance recovery. However, the use of a BNS does not result in the COM moving further back at recovery time.

We know that with age, responses to balance disturbances change: older adults use smaller, multiple steps to respond to a balance disturbance where young adults use a single larger step (Luchies, Alexander, Schultz, & Ashtonmiller, 1994; Maki & McIlroy, 2005; McIlroy & Maki, 1996). As balance further deteriorates with PD, we start to see the use of multiple APAs. Is the use of the BNS a strategy to compensate for the slow response when using multiple APAs, or is it a further deterioration of the response? Could it be related to a difficulty in changing set or an un-needed change in set (set refers to the state of the nervous system that is determined or influenced by the context of a task (Chong et al., 2000))? These questions should be addressed in further studies.

Finally, in this study we did not see a correlation between fall history or the UPDRS scores and the use of a base-width neutral step. This may be due to the small sample size and homogeneity of the PD group (selected for the presence of postural instability). Further studies should investigate the presence of this strategy in other PD severity groups.

### Limitations

This study has limitations. For one, the small sample size and inconsistency in stepping strategies used for each participant yield small numbers when further divided by strategy type. In addition, only moderate PD was investigated. Further study on this topic should include a mild PD group to better understand the evolution of stepping strategies and their effect on balance recovery.

### Conclusions

Moderate PD significantly increases the time required for balance recovery in response to a backwards pull. In addition, the type of strategy used to respond to the disturbance significantly impacts this recovery time. Finally, the use of a BNS as the first step in the response is a new response that has not been previously documented and significantly increases the time to balance recovery.

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**Table 5.1. Characteristics of PD Participants**

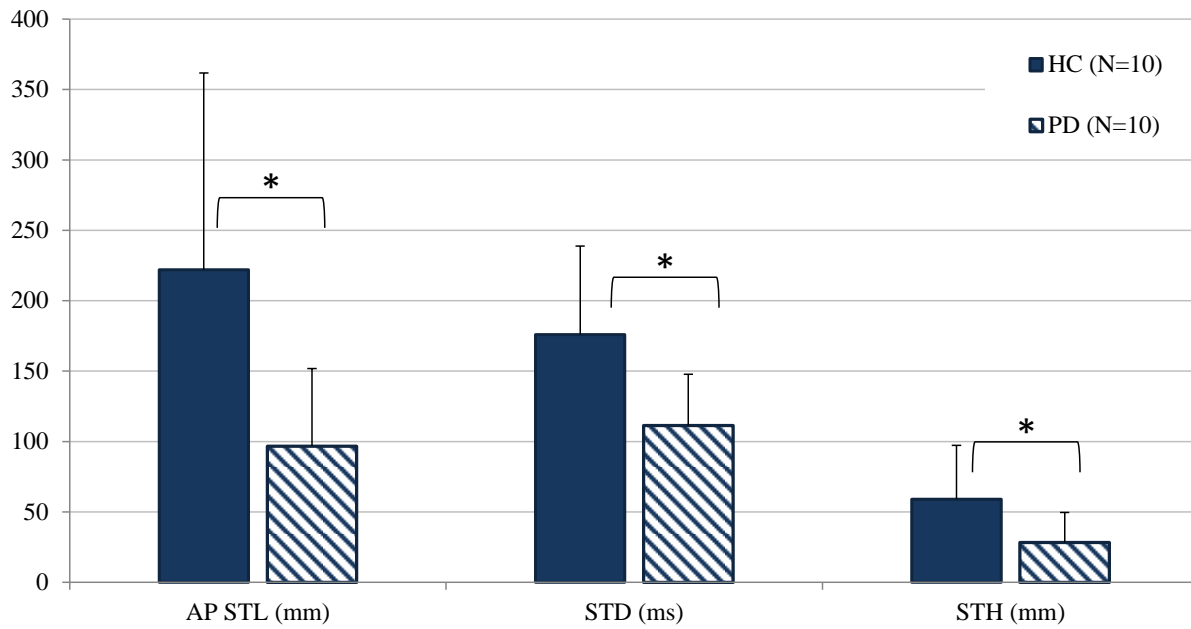
<b>Sub Num</b>	<b>Age</b>	<b>Sex</b>	<b>UPDRS</b>	<b>UPDRS Motor</b>	<b>UPDRS #33</b>	<b>H&amp;Y</b>	<b>Duration (yrs)</b>	<b>Medications</b>	<b>Dose/Day (mg/day)</b>
4002	71	F	47	28	2	3	13	Carbidopa/Levodopa	600
								Carbidopa/Levodopa ER	200
								Pramipexole	1.5
4004	61	M	36	17	2	3	11	Carbidopa/Levodopa	1200
								Entacapone	1200
								Rasagiline	1
								Ropinirole PR	12
4005	69	M	57	36	2	3	3	Carbidopa/Levodopa	750
								Carbidopa/Levodopa ER	100
								Ropinirole	9
4006	71	M	47	27	2	3	7	Carbidopa/Levodopa	800
								Entacapone	800
								Rasagiline	1
								Pramipexole	3
								Amantadine	100
4007	66	M	35	23	2	3	2	Carbidopa/Levodopa	600
								Pramipexole	6
4008	63	M	65	41	2	3	9	Carbidopa/Levodopa	450
								Carbidopa/Levodopa ER	200
								Ropinirole	6
								Amantadine	200
4010	64	M	44	31	2	3	9	Carbidopa/Levodopa	400
								Carbidopa/Levodopa ER	800
								Ropinirole	6
4011	68	M	53	30	2	3	11	Carbidopa/Levodopa	1000
								Ropinirole	9
								Amantadine	200
								Benzotropine	1
4012	72	F	50	33	2	3	8	Carbidopa/Levodopa	800
								Carbidopa/Levodopa ER	700
								Pramipexole	1.5
4013	72	M	62	41	2	3	5	Carbidopa/Levodopa	400
								Amantadine	100/week
<b>Average</b>	<b>67.7</b>		<b>49.6</b>	<b>30.7</b>	<b>2</b>	<b>3</b>	<b>7.8</b>		
<b>Std Dev</b>	<b>4.00</b>		<b>10.00</b>	<b>7.56</b>	<b>0.00</b>	<b>0.00</b>	<b>3.58</b>		

**Table 5.2. Characteristics of Participant Groups, Pull and Initial Stance Characteristics**

	<b>HC (N = 10)</b>	<b>PD (N = 10)</b>	<b>p-value</b>
<b>Age (yrs)</b>	68 (5)	68 (4)	0.677
<b>Mass (kg)</b>	75 (13)	85 (19)	0.192
<b>Height (cm)</b>	175 (6)	173 (10)	0.507
<i>Pull Characteristics</i>			
<b>Peak (N)</b>	299 (57)	290 (59)	0.737
<b>Duration (ms)</b>	304 (15)	308 (34)	0.682
<b>Impulse/wh (N-s/kg-m)</b>	.251 (.04)	.232 (.06)	0.456
<i>Initial Stance Characteristics</i>			
<b>Stance Width (mm)</b>	231 (38)	248 (63)	0.455
<b>COP AP at Pull (mm)</b>	-.312 (1.9)	2.27 (5.37)	0.179
<b>COP ML at Pull (mm)</b>	.015 (1.37)	.823 (2.76)	0.418
<b>Left Vertical Force at Pull (N)</b>	394 (81)	450 (113)	0.216
<b>Right Vertical Force at Pull (N)</b>	393 (61)	431 (97)	0.241

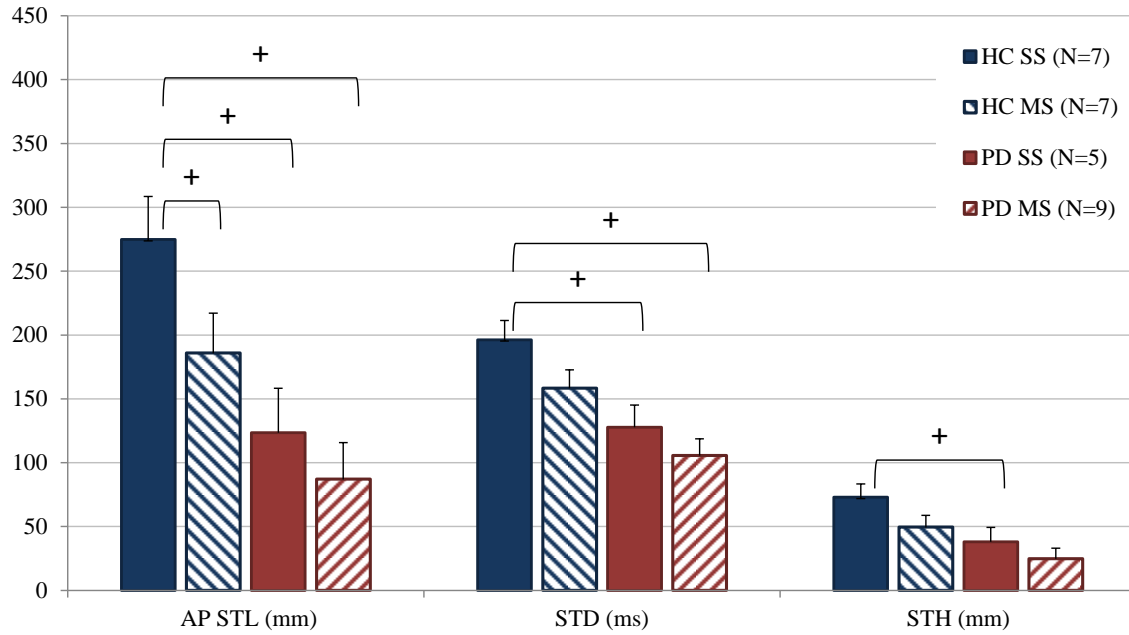
Participant characteristics, pull characteristics, and initial stance characteristics showed no significant differences. Values are mean (standard deviation). P-values are based on t-tests.

**Figure 5.1. Comparison of Step Characteristics in HC Group Compared to PD Group**



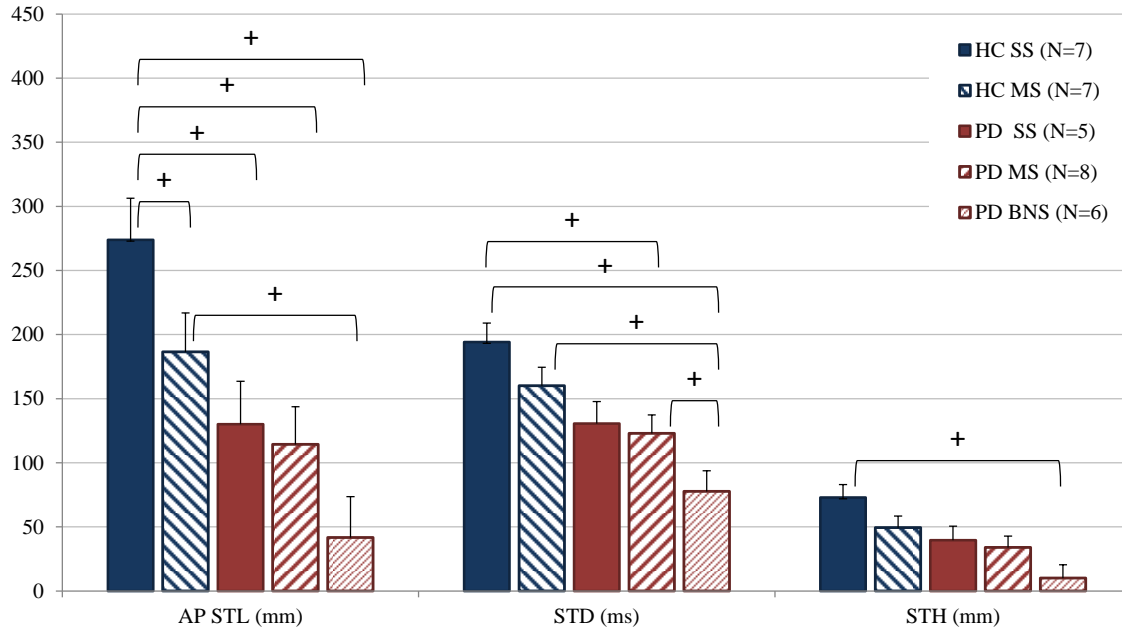
Comparison of step characteristics in HC group compared to PD group. All response types are included (single step, multiple step, base-width neutral step). Bars are means + standard deviation. \* indicates  $p < .05$  in Mann-Whitney U-Test. AP STL= step length in the anterior-posterior direction, STD= step duration time, STH= step height.

**Figure 5.2. Comparison of Step Characteristics in HC And PD Group by Strategy Category**



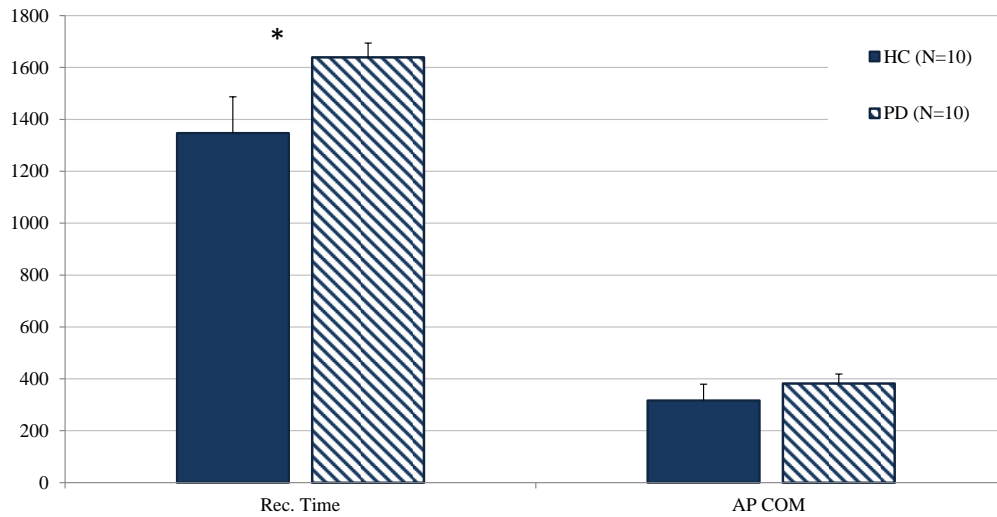
Comparison of step characteristics in HC and PD group by strategy category. HC SS= healthy control single step, HC MS= healthy control multiple step, PD SS= PD single step, PD MS= PD multiple step. Bars are means + SE. + indicates pairwise  $p < .05$  after Bonferroni correction based on Linear Mixed Model. AP STL= step length in the anterior-posterior direction, STD= step duration time, STH= step height.

**Figure 5.3. Comparison of Step Characteristics in HC and PD Group by Strategy Category**



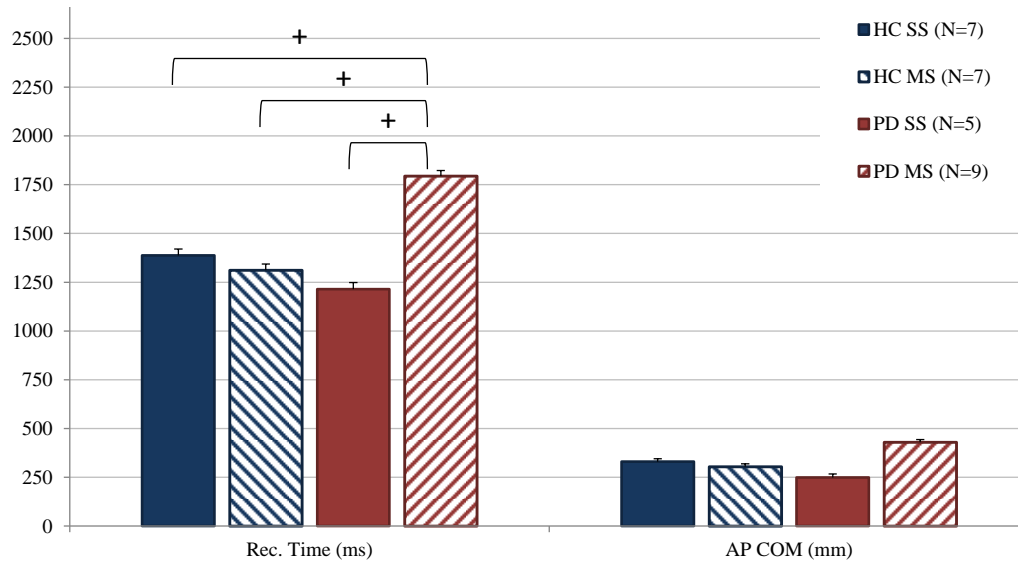
Comparison of step characteristics in HC and PD group by strategy category. HC SS= healthy control single step, HC MS= healthy control multiple step, PD SS= PD single step, PD MS= PD multiple step, PD BNS= PD base-width neutral step. Bars are means + SE. + indicates pairwise  $p < .05$  after Bonferroni correction based on Linear Mixed Model. AP STL= Anterior-Posterior Step Length, STD= step duration time, STH= step height.

**Figure 5.4. Comparison of Balance Recovery Parameters in HC Group Compared to PD Group**



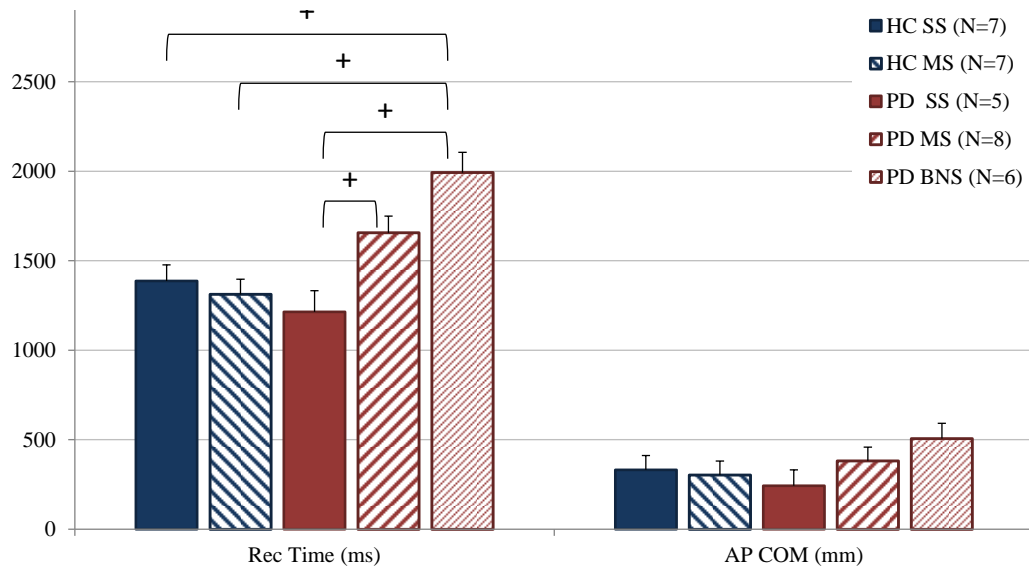
Comparison of balance recovery parameters in HC group compared to PD group. All response types are included (SS, MS, BNS). Bars are means + SE. \* indicates  $p < .05$  based on t-test. Rec Time = time to balance recovery, AP COM= position of the center of mass in the anterior-posterior direction at time of balance recovery.

**Figure 5.5. Comparison of Balance Recovery Parameters by Single vs. Multiple Step Strategy**



Comparison of step characteristics in HC and PD group by strategy category. HC SS= healthy control single step, HC MS= healthy control multiple step, PD SS= PD single step, PD MS= PD multiple step. Bars are means + SE. + indicates pairwise  $p < .05$  after Bonferroni correction in Linear Mixed Model. Rec Time = time to balance recovery, AP COM= position of the center of mass in the anterior-posterior direction at time of balance recovery.

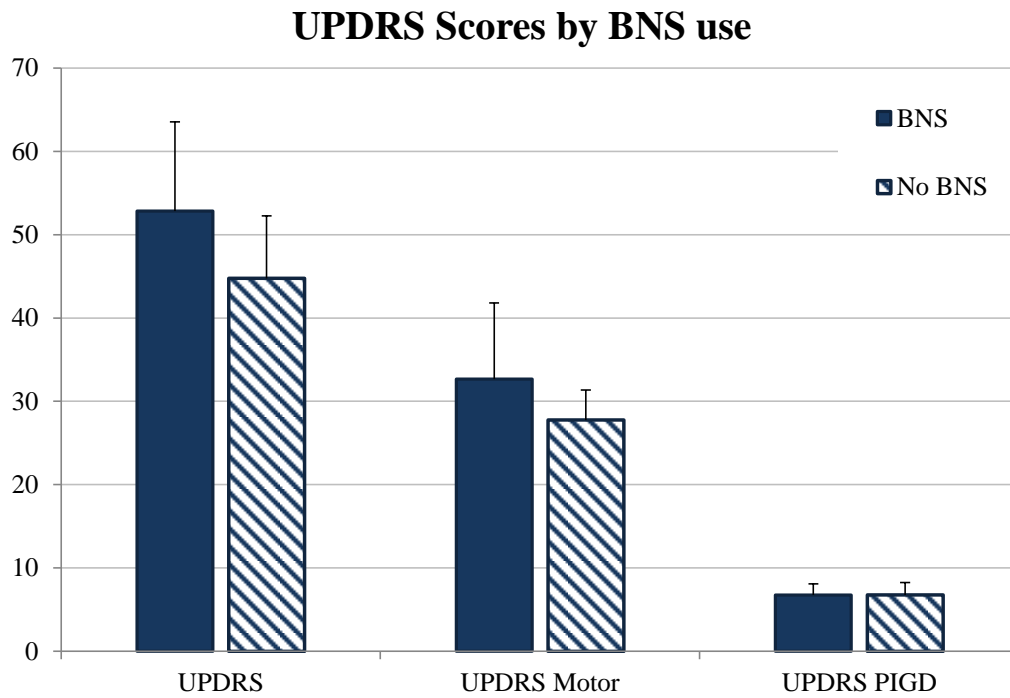
**Figure 5.6. Comparison of Balance Recovery Parameters by Strategy Category**



Comparison of step characteristics in HC and PD group by strategy category. HC SS= healthy control single step, HC MS= healthy control multiple step, PD SS= PD single step, PD MS= PD multiple step, PD BNS= PD base-width neutral step. Bars are means + SE. + indicates pairwise  $p < .05$  after Bonferroni correction in linear mixed model. Rec Time = time to balance recovery, AP COM= position of the center of mass in the anterior-posterior direction at time of balance recovery.

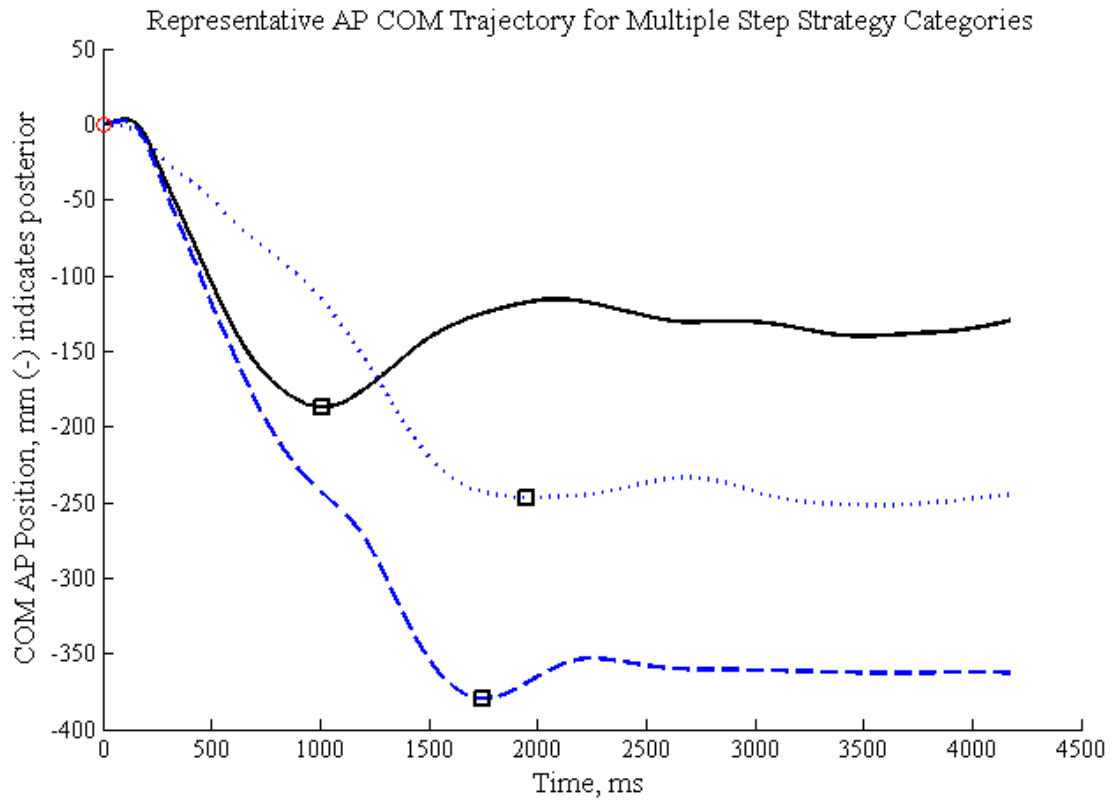


**Figure 5.7. UPDRS Scores by Strategy Type (use of BNS or no use of BNS)**



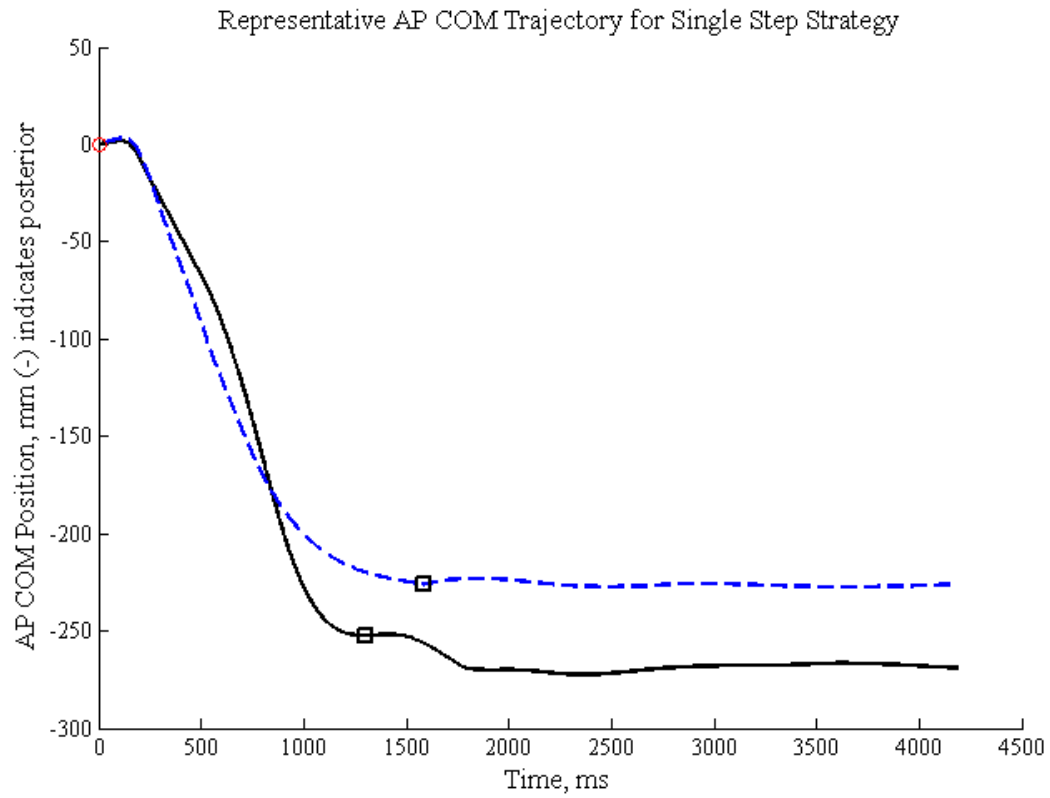
UPDRS scores by BNS use. BNS= base-width neutral step used as first step in response. UPDRS= Unified Parkinson's Disease Rating Scale, PIGD= Postural instability and Gait Disorder subsection of UPDRS.

**Figure 5.8. Representative Trace of AP COM Trajectory in Multiple Step Strategy Category**



Representative trace of AP COM trajectory in multiple step strategy categories. Solid black line= healthy control multiple step trial, dashed blue line= PD multiple step trial, dotted blue line= PD base-width neutral step trial. Circle indicates disturbance onset, squares indicate balance recovery time.

**Figure 5.9. Representative Trace of AP COM Trajectory in Single Step Strategy Category**



Representative trace of AP COM trajectory in single step strategy categories. Solid black line= healthy control single step trial, dashed blue line= PD single step trial. Circle indicates disturbance onset, squares indicate balance recovery time.

## CHAPTER SIX: SUMMARY

### *Summary of Study*

The primary goal of this work was to investigate the effect of moderate Parkinson's disease on compensatory backwards stepping after a balance disturbance. Healthy control (HC) participants and participants with moderate Parkinson's disease (PD) responded naturally to a backwards pull at the waist. Video, motion, EMG, force plate, and load cell data were used to quantify the response in terms of strategy, temporal, kinematic, kinetic, and center of pressure parameters.

The first study investigated the overall response to a balance disturbance in moderate PD, looking at strategy, temporal, kinematic, and center of pressure parameters during the first step in the response. Patients with moderate PD utilized more steps to regain balance, had a longer weight shift time, and the use of a base-width neutral step emerged as a strategy used to regain balance.

The second study further investigated the compensatory response by focusing on the preparation phase, specifically looking at the movement of the center of pressure and the use of anticipatory postural adjustments prior to liftoff of the first step. Moderate PD significantly affected the preparation for the first compensatory step. PD participants used multiple APAs, resulting in longer liftoff times and significantly different movement in the center of pressure prior to liftoff compared to healthy controls. Furthermore, the differences in the response could be attributed to the stage of preparation prior to final weight shift. This portion of the response and these parameters should be further investigated for their value in the development of a more sensitive measure of postural instability.

The third study described the effects of moderate PD on balance recovery time and the position of the center of mass at balance recovery, and investigated the effects of step strategy (single step, multiple steps, and a base-width neutral step) on balance recovery. Participants with moderate PD took

significantly longer to recover balance in response to the backwards pull. In addition, the type of strategy used to respond to the disturbance was found to significantly impact the length of the recovery time. Finally, the use of a base-width neutral step as the first step in the response emerged as a new response that has not been previously documented and significantly delays the length of time required to achieve balance recovery.

### *Conclusions and Recommendations*

Taken together, the results from these studies suggest that moderate Parkinson's disease significantly impairs the compensatory response to a backwards pull. In particular, participants with moderate PD used more steps to regain balance and a longer weight shift time. Furthermore, this impairment could be attributed, at least in part, to a delay in the preparation phase of the step response. This delay was associated with the use of multiple anticipatory postural adjustments and/or the use of a base-width neutral step as the first step in the response. As suggested by other studies, it may be that this impairment in preparation for the step is due to the interruption of a pre-planned response that is not working fast enough to stabilize the center of mass. It is unclear whether or not these impairments are associated with an increased risk of falling, a question which is beyond the scope of the current study. Further study should examine the progression of impairment in these compensatory responses across severity levels, and the correlation with fall risk.

### *Limitations and Future Work*

This study has limitations. For one, subjects were only tested in the ON medication state. We do not have data to describe the effects of medication on this response. However, the long-term goal of this research is to determine biomechanical tests that can be adapted for clinical use, in which case the patients would be tested on their normal medication. Another limitation of this study is the small sample size, particularly when groups were further divided based on preparation strategy. It is noted that the linear

mixed model analyses are exploratory, and care has been taken to be conservative in interpretation of all results.

Future studies must address several questions. First, how do the responses in moderate PD correspond to other disease severity levels, specifically mild PD? Are the differences seen in these studies a further deterioration of the response in mild PD or are the changes in strategy such as the use of a base-width neutral step a compensatory strategy developed as PD progresses? The progression of these changes in compensatory strategies must be further explored. Second, how do these changes in compensatory response correlate to postural instability and fall risk? Finally, is there a biomechanical measure or a set of measures that can add more sensitivity and specificity to the current clinical evaluation of postural instability in Parkinson's disease, and if so, how can the quantitative measures be translated to the clinic?

## APPENDIX A: DETAILED DESCRIPTION OF OUTCOME MEASURE CALCULATIONS

## **Paper 1: Effect of Moderate Parkinson's Disease on the Step Response to a Backwards Pull**

*Strategic Parameters:* Qualitative differences in the strategy used to recover from the balance disturbance were determined by analyzing video recorded during the trials. Parameters extracted from the video recordings include: the number of steps taken to regain balance, utilization of a single or multiple step response, and the foot used for the first step (right or left). A participant was defined as a multiple step user if a multiple step response was used to regain balance in any of the three trials. A participant was classified as being step foot consistent if the same foot was used for the first step in all three trials. A trial was defined as a change-in-the-base-of-support if the foot lifted off the force plate and repositioned to change the base of support. The foot was required to translate 50mm or more (as calculated by the difference in position between liftoff and landing of the heel marker) in order to be considered a step.

*Data Conditioning:* Analog data (force plate, load cell, and EMG) were first zeroed by subtracting off the mean of a 1 second zero trial, taken just prior to the start of data collection. Then data was filtered with a second-order low pass Butterworth filter with a cutoff frequency of 20 Hz for the force plate signal and 50 Hz for the EMG signals and load cell signals.

*Coordinate Systems:* All force plate data was rotated to coincide with the global coordinate system for the optotrak system (see Figure A-1). The origin of the global coordinate system was at the back right corner of the back force plate, with positive X pointing anterior and positive Y pointing medial when standing on the back force plate facing north.

*Temporal Parameters:* A threshold method was used to determine four temporal events (disturbance onset, EMG onset, and step foot liftoff and landing times) which were used to define the temporal parameters reaction time, weight shift time and step duration. The following parameters and definitions were used.



*Disturbance onset:* The cable pull force was measured using a bi-axial load cell. Disturbance onset ( $LC_{onset}$ ) was defined as the time when the total load cell force exceeded the threshold. The total load cell force was taken as

$$Total\ LC_{force} = \sqrt{LC_{normal}^2 + LC_{shear}^2} \text{ (in N)}$$

The load cell threshold was defined as the mean plus 10 standard deviations of the signal over the first 500ms of data collection.

*Muscle onset:* EMG signals for the right and left Tibialis Anterior (TA) muscle were analyzed. Signals were full-wave rectified, the mean was subtracted, and then the signal was low pass filtered with a cutoff frequency of 50 Hz. The EMG threshold value was defined as the mean plus five standard deviations of the signal over a 50 ms window prior to the disturbance. Muscle onset ( $EMG_{on}$ ) was defined as the first time 25 consecutive EMG data points exceeded the threshold in either the right or left muscle, whichever happened first.

*Reaction time (RT):* time between disturbance onset and first TA muscle onset.

$$RT = EMG_{on} - LC_{onset} \text{ (in ms)}$$

*Liftoff time (LT):* time between disturbance onset and unloading of the vertical force component under the foot used for stepping, when the vertical force is less than 4% body weight.

*Weight shift time (WST):* time between reaction time and liftoff time.

$$WST = LT - LC_{onset} \text{ (in ms)}$$

*Landing time (LDT):* time between disturbance onset and re-loading of the vertical force component under the foot used for stepping, when the vertical force is greater than 4% body weight.

*Step duration (STD):* time between landing time and liftoff time.

$$STD = LDT - LT \text{ (in ms)}$$

*Ankle Kinematics:* The ankle angle was determined using the measured motion data with the kinematics portion of Vaughn's 3D inverse dynamics model. The segments used were the right and left foot and calf. First, unit vectors for each segment were determined based on marker placement, and joint centers for the

toe, ankle, and knee were established based on anthropometrics and the unit vectors. Next, a segment reference frame was determined for the calf and foot using the joint centers and the appropriate markers. Finally, the plantarflexion angle was determined as the angle between the calf and foot segments (see Appendix B for details on kinematic model).

The peak ankle plantarflexion/dorsiflexion angle during the initial stage of the response (prior to liftoff) and the angle at liftoff of the first step was extracted and expressed relative to the initial configuration. The excursion was taken as the maximum plantarflexion plus the maximum dorsiflexion. The initial angle was taken as the mean of the angle for the 50ms prior to disturbance onset.

*Center of Pressure (COP) Displacement:* The anterior-posterior (AP) and medial-lateral (ML) COP locations were calculated as a function of time using the foot/floor reaction forces and moments. First, the COP for each individual force plate was calculated using the following equations:

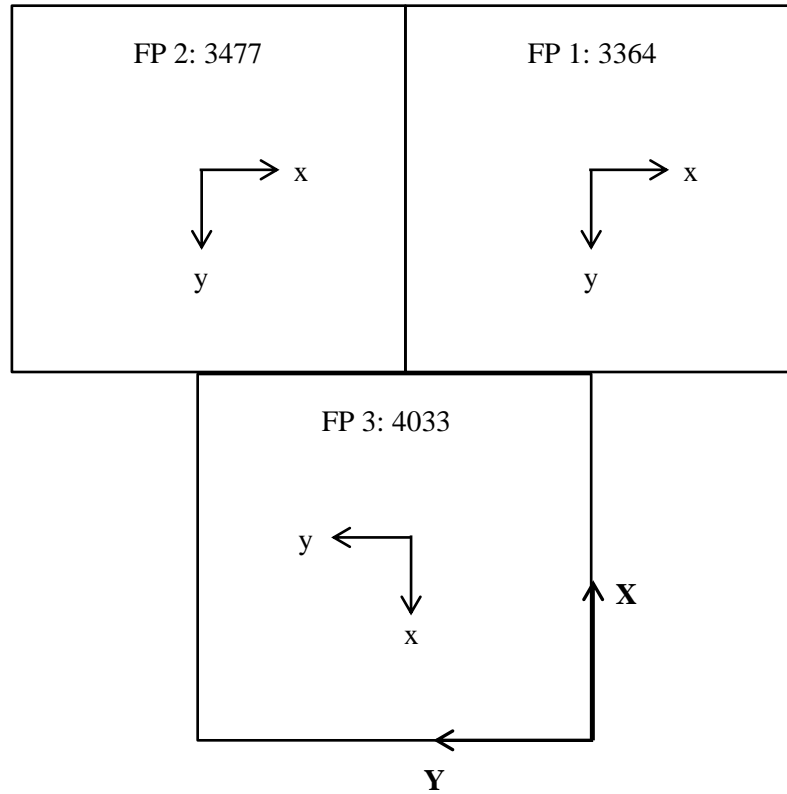
$$COP_x = \frac{-(My + Fx * dz)}{Fz}$$

$$COP_y = \frac{(Mx - Fy * dz)}{Fz}$$

Where  $M_x$ ,  $M_y$ ,  $F_x$ , and  $F_z$  are the components of the force plate output, and  $dz$  indicates the vertical distance from each plate's surface to its coordinate system origin. In our global coordinate system,  $x$  indicates the anterior-posterior direction and  $y$  indicates the medial-lateral direction. At this point all force plates have the same coordinate system orientation (the global orientation). Next, the force plate coordinate systems need to be translated to coincide with the global origin using measurements of the distance between each individual force plate origin and the global origin, using the method outlined by Kistler (see figure A-2).

The whole-body COP location was analyzed from disturbance onset time to landing of the first step. The AP and ML displacements of the COP were determined at liftoff and landing of the first step relative to the COP location at disturbance onset.

**Figure 6.1. Illustration of Laboratory Coordinate Systems**



Schematic of Laboratory Coordinate Systems. Lower-case letters represent force plate local coordinate systems, bold capital letters represent Optotrak global coordinate system.

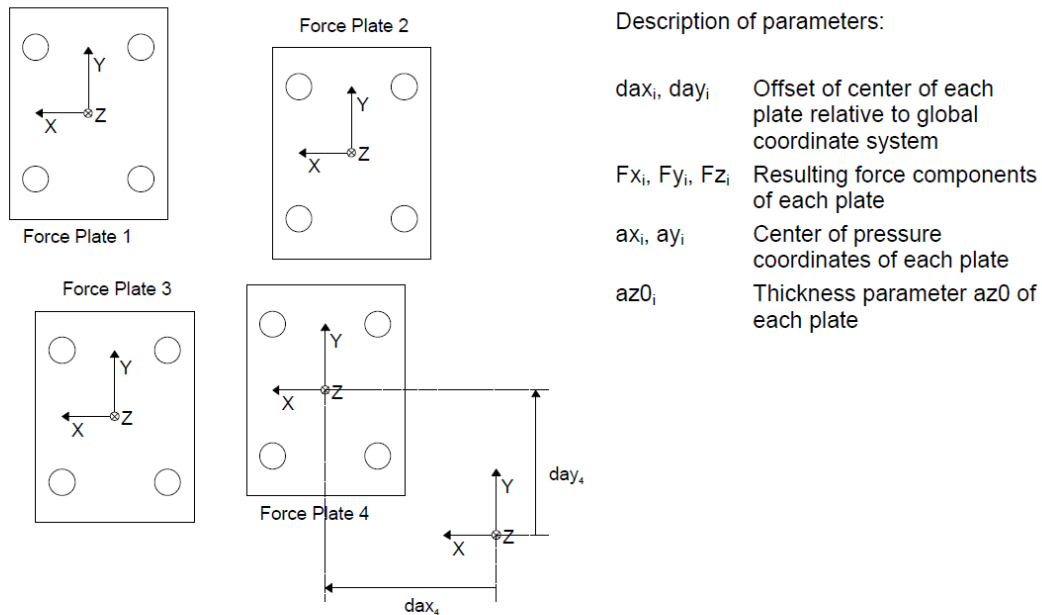
**Figure 6.2. Description of Method to Calculate COP from Multiple Force Plates**

### Global coordinate system (treat multiple force plates as one)

The following formulae are used if one or several force plates have to be transformed into one global coordinate system and if several force plates have to be treated as one large plate.

A global coordinate system has to be defined relative to which the center of each force plate is offset by  $dax$ ,  $day$ .

If a force plate is not only offset but also rotated, a coordinate transformation (rotation) around its center has to be performed (see preceding chapter). This brings the data of the force plate data into the same direction as the reference coordinate system.



Global Parameter	Calculation
$Fx$	$= Fx_1 + Fx_2 + \dots + Fx_n$
$Fy$	$= Fy_1 + Fy_2 + \dots + Fy_n$
$Fz$	$= Fz_1 + Fz_2 + \dots + Fz_n$
$Mx$	$= (day_1 + ay_1) * Fz_1 + (day_2 + ay_2) * Fz_2 + \dots + (day_n + ay_n) * Fz_n$
$My$	$= -(dax_1 + ax_1) * Fz_1 - (dax_2 + ax_2) * Fz_2 - \dots - (dax_n + ax_n) * Fz_n$
$Mx'$	$= Mx + az0_1 * Fy_1 + az0_2 * Fy_2 + \dots + az0_n * Fy_n$
$My'$	$= My - az0_1 * Fx_1 - az0_2 * Fx_2 - \dots - az0_n * Fx_n$
$ax$	$= -My' / Fz$
$ay$	$= Mx' / Fz$
$Mz$	$= [(dax_1 + ax_1) * Fy_1 - (day_1 + ay_1) * Fx_1] + \dots + [(dax_n + ax_n) * Fy_n - (day_n + ay_n) * Fx_n]$
$Tz$	$= Mz - Fy * ax + Fx * ay$

## **Paper 2: Preparation for Compensatory Backwards Stepping in Moderate Parkinson's Disease**

*Data Conditioning:* Analog data (force plate, load cell, and EMG) were first zeroed by subtracting off the mean of a 1 second zero trial, taken just prior to the start of data collection. Then data was filtered with a second-order low pass Butterworth filter with a cutoff frequency of 20 Hz for the force plate signal and 50 Hz for the EMG signals and load cell signals.

*Coordinate Systems:* All force plate data was rotated to coincide with the global coordinate system for the optotrak system (see figure A-1). The origin of the global coordinate system was at the back right corner of the back force plate, with positive X pointing anterior and positive Y pointing medial when standing on the back force plate facing north.

*Center of Pressure (COP) Parameters:* The anterior-posterior (AP) and medial-lateral (ML) COP locations were calculated as a function of time using the foot/floor reaction forces and moments. First, the COP for each individual force plate was calculated using the following equations:

$$COP_x = \frac{-(My + Fx * dz)}{Fz}$$

$$COP_y = \frac{(Mx - Fy * dz)}{Fz}$$

Where  $M_x$ ,  $M_y$ ,  $F_x$ , and  $F_z$  are the components of the force plate output, and  $dz$  indicates the vertical distance from each plate's surface to its coordinate system origin. In our global coordinate system,  $x$  indicates the anterior-posterior direction and  $y$  indicates the medial-lateral direction. At this point all force plates have the same coordinate system orientation (the global orientation). Next, the force plate coordinate systems need to be translated to coincide with the global origin using measurements of the distance between each individual force plate origin and the global origin, using the method outlined by Kistler (see figure A-2).

*Definition of Response Stages:* This paper focused on the preparation phase of the response- prior to liftoff of the first step. So, the whole-body COP was analyzed from disturbance onset until liftoff of the first step. Within this phase, two stages were defined. The first phase was defined as disturbance onset until the start of the final weight shift, and phase two was defined as from the start of final weight shift to liftoff of the first step. The start of final weight shift was defined as the last time the ML COP changed direction, and was calculated by looking for the last change in sign of the derivative of the ML COP signal. The following parameters were calculated for each stage:

*COP Path Length:* Path length was defined as the total distance traveled by the COP and calculated as the sum of the difference in location of each point in the COP in each direction, as below where m is taken as the length of the COP vector.

$$AP \text{ Path Length} = \sum_{i=1}^{i=m-1} COP_{AP}(i+1) - COP_{AP}(i)$$

$$ML \text{ Path Length} = \sum_{i=1}^{i=m-1} COP_{ML}(i+1) - COP_{ML}(i)$$

*COP Displacement:* COP displacement was defined as the difference in COP location between the start and end of each stage.

*Duration:* Duration of each stage was calculated as the time between the start and end of each stage.

*Average Velocity:* The average velocity of the AP and ML COP was calculated as the path length divided by duration of the stage.

*Anticipatory Postural Adjustments:* Anticipatory postural adjustments were defined similarly to the method in Jacobs and McIlroy. APAs were determined by looking at the ML COP signal from 500 ms prior to onset of the disturbance to liftoff of the first step. The baseline signal was defined by the average of the signal for 500 ms prior to onset of the disturbance. Local maximums and minimums were defined if

the ML COP traveled more than 1 cm from the baseline. Each maximum and minimum indicated the presence of an APA. However, two rules were established to prevent incorrectly identifying additional APAs: a subsequent APA was required to be in the opposite direction of the first, and an APA was not counted if the local maximum or minimum occurred just prior to liftoff. Visual inspection verified the Matlab-counted APAs, and trials were classified as having 0, 1, or 2 or more APAs.

### **Paper 3: The Effect of the use of a Base-Width Neutral Step on Balance Recovery in Parkinson's Disease**

*Data Conditioning:* Analog data (force plate, load cell, and EMG) were first zeroed by subtracting off the mean of a 1 second zero trial, taken just prior to the start of data collection. Then data was filtered with a second-order low pass Butterworth filter with a cutoff frequency of 20 Hz for the force plate signal and 50 Hz for the EMG signals and load cell signals.

*Coordinate Systems:* All force plate data was rotated to coincide with the global coordinate system for the optotrak system (see Figure A-1). The origin of the global coordinate system was at the back right corner of the back force plate, with positive X pointing anterior and positive Y pointing medial when standing on the back force plate facing north.

*Center of Pressure (COP) Parameters:* The anterior-posterior (AP) and medial-lateral (ML) COP locations were calculated as a function of time using the foot/floor reaction forces and moments. First, the COP for each individual force plate was calculated using the following equations:

$$COP_x = \frac{-(My + Fx * dz)}{Fz}$$

$$COP_y = \frac{(Mx - Fy * dz)}{Fz}$$

Where Mx, My, Fx, and Fz are the components of the force plate output, and dz indicates the vertical distance from each plate's surface to its coordinate system origin. In our global coordinate system, x indicates the anterior-posterior direction and y indicates the medial-lateral direction. At this point all force plates have the same coordinate system orientation (the global orientation). Next, the force plate coordinate systems need to be translated to coincide with the global origin using measurements of the distance between each individual force plate origin and the global origin, using the method outlined by Kistler (see figure A-2).



*Estimation of Center of Mass:* The position of the center of mass was approximated by double integration of the lateral ground reaction forces:

$$\vec{v} = \int \frac{\vec{F}}{m} + v_o$$

$$\vec{p} = \int \vec{v} + p_o$$

Where F= the horizontal GRFs, m is the mass of the participant, v is the velocity of the center of mass, p is the position of the center of mass, vo is the initial velocity of the COM, assumed to be zero at disturbance onset, and po is the initial position of the center of mass, assumed to be equal to the COP at load cell onset. To combat against amplification of noise, data was detrended after the first integration.

## APPENDIX B : KINEMATIC MODEL DETAILS<sup>1</sup>

<sup>1</sup>Modified from Vaughan, C.L., B.L. Davis, and J.C. O'Connor, *Dynamics of Human Gait*. 1992,  
Champaign, IL: Human Kinetics Publishers.

## APPENDIX B

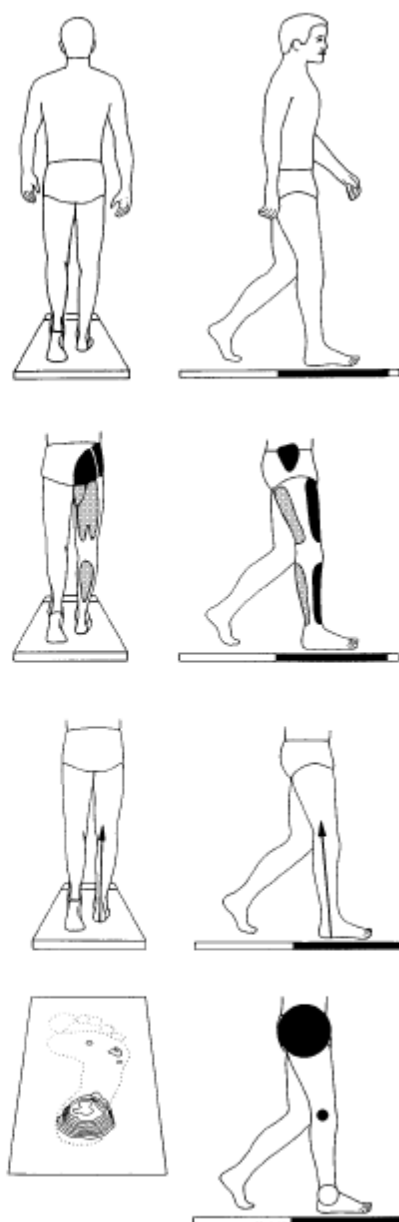
# Detailed Mathematics Used in *GaitLab*

This appendix contains the detailed mathematics that are used to process the anthropometric, kinematic, and force plate data files. These details have been incorporated in the *GaitLab* program. Because we do not provide a listing of the source code for *GaitLab*, and because the material presented in chapter 3 tends to gloss over many details, we have provided all the necessary details for researchers of human gait in this appendix.

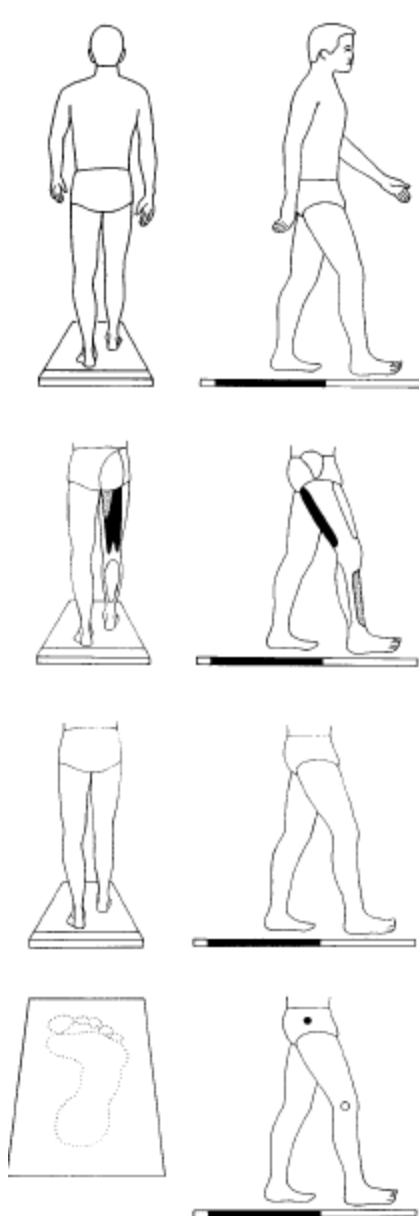
Like chapter 3, this appendix covers five different topics: body segment parameters; linear kinematics; centres of gravity; angular kinematics; and dynamics of joints.

### Body Segment Parameters

We have chosen to use a method for predicting body segment parameters that is based on simple geometric modeling combined with the anthropometric data of Chandler *et al.* (1975). The thighs and calves are modelled by right rectangular cylinders, whereas the feet are modelled by right rectangular pyramids. The key point to bear in mind is that our modelling process makes use of dimensional consistency. By this we mean that only parameters that have the composite units of kilograms are used to predict segment mass, and that only parameters with the composite units of  $\text{kg}\cdot\text{m}^2$  are used to predict segmental moments of inertia. We believe, for example, that it makes little sense to use only total body mass to predict segmental moments of inertia. (This was the method used by Chandler *et al.*, 1975.) We will show later in this section how much better our method is in predicting segment moments of inertia.



Frame = 4  
Time = 0.12 s



Frame = 28  
Time = 1.08 s

Equations 3.1 to 3.3 describe the format and rationale for generating regression equations to predict segment mass based on anthropometric data. The relevant parameters,  $A_1$  through  $A_{20}$ , are presented in Table B.1. (A description of how to make these measurements is provided in Table 3.1.) The regression equations that we derived (Equations 3.4 to 3.6 in chapter 3) are based on the six cadavers in Chandler *et al.* (1975) and are repeated here, for sake of completeness, in Table B.2. This table also lists the centre of gravity ratios, which are based on the mean values of the cadavers.

In equations 3.7 to 3.10 and Figure 3.3 we argued for regression equations to predict segmental moments of inertia that are based on body mass in kilograms (kg) times a composite parameter having the dimensions of length squared ( $m^2$ ). Equation 3.11 was presented as one example (in this case, for the moment of inertia of the thigh about the flexion/extension axis) of such a regression equation. The full set of 18 equations (right and left thighs, calves, and feet, about their flexion/extension, abduction/adduction, internal/external rotation axes) is presented in Table B.3. In trying to understand the relevant axes, refer to Figure 3.3 and 3.10 and the following key:

FlxExt = z axis  
AbdAdd = y axis  
IntExt = x axis

**Table B.1 Anthropometric Data for Calculating Body Segment Parameters and for Predicting Joint Centres and Segment Endpoints**

Parameter number	Name
$A_1$	Total body mass
$A_2$	Anterior superior iliac spine (ASIS) breadth
$A_3$	Right thigh length
$A_4$	Left thigh length
$A_5$	Right midthigh circumference
$A_6$	Left midthigh circumference
$A_7$	Right calf length
$A_8$	Left calf length
$A_9$	Right calf circumference
$A_{10}$	Left calf circumference
$A_{11}$	Right knee diameter
$A_{12}$	Left knee diameter
$A_{13}$	Right foot length
$A_{14}$	Left foot length
$A_{15}$	Right malleolus height
$A_{16}$	Left malleolus height
$A_{17}$	Right malleolus width
$A_{18}$	Left malleolus width
$A_{19}$	Right foot breadth
$A_{20}$	Left foot breadth

**Table B.2 Equations to Predict the Masses and Centres of Gravity for the Thigh, Calf and Foot**

$$\begin{aligned} \text{Mass.R.Thigh} &= (0.1032) * A1 + (12.76) * A3 * A5 * A5 - 1.023; \\ \text{Mass.L.Thigh} &= (0.1032) * A1 + (12.76) * A4 * A6 * A6 - 1.023; \\ \text{Mass.R.Calf} &= (0.0226) * A1 + (31.33) * A7 * A9 * A9 + 0.016; \\ \text{Mass.L.Calf} &= (0.0226) * A1 + (31.33) * A8 * A10 * A10 + 0.016; \\ \text{Mass.R.Foot} &= (0.0083) * A1 + (254.5) * A13 * A15 * A17 - 0.065; \\ \text{Mass.L.Foot} &= (0.0083) * A1 + (254.5) * A14 * A16 * A18 - 0.065; \end{aligned}$$

$$\begin{aligned} \text{CG\_Ratio.R.Thigh} &= 0.39; \\ \text{CG\_Ratio.L.Thigh} &= 0.39; \\ \text{CG\_Ratio.R.Calf} &= 0.42; \\ \text{CG\_Ratio.L.Calf} &= 0.42; \\ \text{CG\_Ratio.R.Foot} &= 0.44; \\ \text{CG\_Ratio.L.Foot} &= 0.44; \end{aligned}$$

*Note.* A1 through A18 are the anthropometric parameters defined in Table B.1. The format of these equations is exactly the same as the C++ code in *GaitLab*.

**Table B.3 Equations to Predict Moments of Inertia (I) for the Thigh, Calf, and Foot**

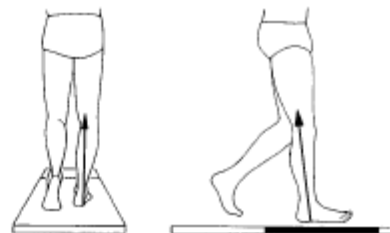
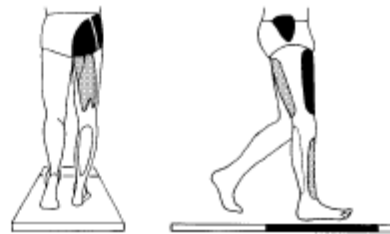
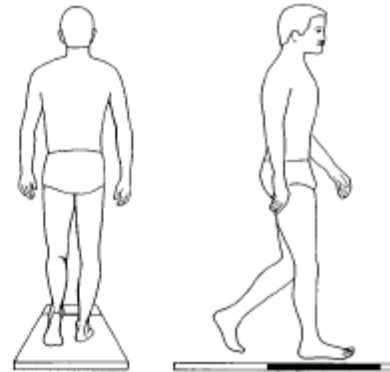
$$\begin{aligned} I_{\text{FlxExt.R.Thigh}} &= 0.00762 * A1 * (A3 * A3 + 0.076 * A5 * A5) + 0.01153; \\ I_{\text{FlxExt.L.Thigh}} &= 0.00762 * A1 * (A4 * A4 + 0.076 * A6 * A6) + 0.01153; \\ I_{\text{AbdAdd.R.Thigh}} &= 0.00726 * A1 * (A3 * A3 + 0.076 * A5 * A5) + 0.01186; \\ I_{\text{AbdAdd.L.Thigh}} &= 0.00726 * A1 * (A4 * A4 + 0.076 * A6 * A6) + 0.01186; \\ I_{\text{IntExt.R.Thigh}} &= 0.00151 * A1 * A5 * A5 + 0.00305; \\ I_{\text{IntExt.L.Thigh}} &= 0.00151 * A1 * A6 * A6 + 0.00305; \end{aligned}$$

$$\begin{aligned} I_{\text{FlxExt.R.Calf}} &= 0.00347 * A1 * (A7 * A7 + 0.076 * A9 * A9) + 0.00511; \\ I_{\text{FlxExt.L.Calf}} &= 0.00347 * A1 * (A8 * A8 + 0.076 * A10 * A10) + 0.00511; \\ I_{\text{AbdAdd.R.Calf}} &= 0.00387 * A1 * (A7 * A7 + 0.076 * A9 * A9) + 0.00138; \\ I_{\text{AbdAdd.L.Calf}} &= 0.00387 * A1 * (A8 * A8 + 0.076 * A10 * A10) + 0.00138; \\ I_{\text{IntExt.R.Calf}} &= 0.00041 * A1 * A9 * A9 + 0.00012; \\ I_{\text{IntExt.L.Calf}} &= 0.00041 * A1 * A10 * A10 + 0.00012; \end{aligned}$$

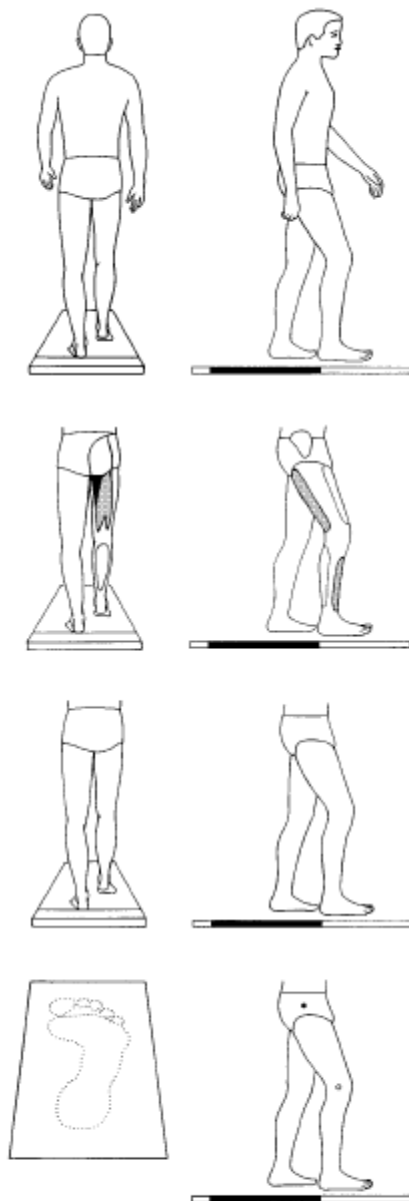
$$\begin{aligned} I_{\text{FlxExt.R.Foot}} &= 0.00023 * A1 * (4 * A15 * A15 + 3 * A13 * A13) + 0.00022; \\ I_{\text{FlxExt.L.Foot}} &= 0.00023 * A1 * (4 * A16 * A16 + 3 * A14 * A14) + 0.00022; \\ I_{\text{AbdAdd.R.Foot}} &= 0.00021 * A1 * (4 * A19 * A19 + 3 * A13 * A13) + 0.00067; \\ I_{\text{AbdAdd.L.Foot}} &= 0.00021 * A1 * (4 * A20 * A20 + 3 * A14 * A14) + 0.00067; \\ I_{\text{IntExt.R.Foot}} &= 0.00141 * A1 * (A15 * A15 + A19 * A19) - 0.00008; \\ I_{\text{IntExt.L.Foot}} &= 0.00141 * A1 * (A16 * A16 + A20 * A20) - 0.00008; \end{aligned}$$

*Note.* A1 through A20 are the anthropometric parameters defined in Table B.1. The format of these equations is exactly the same as the C++ code in *GaitLab*.

Because we have proposed that a gait analyst should take the time to measure 20 anthropometric parameters (Table B.1) and use these data in our regression equations (Tables B.2 and B.3), it is



Frame = 5  
Time = 0.16 s  
Left toe-off



Frame = 24  
Time = 0.92 s

reasonable to ask, Is there any benefit? We believe that there *is* a benefit in personalising the BSPs. Chandler *et al.* (1975) derived regression equations based only on total body mass for predicting segmental masses and moments of inertia. Their correlation coefficients, which are a measure of how well their equations fitted the data, are presented in Table B.4. For comparison, our correlation coefficients are also included in this table. Because Equations 3.4 to 3.6 (top of Table B.2) used more than one parameter to predict segment mass (total body mass and a composite parameter representing segment volume), it is necessary to calculate  $R'$ , the correlation coefficient adjusted to allow for shrinkage:

$$R' = [R^2 - \frac{(p-1)}{N-p} (1-R^2)]^{\frac{1}{2}} \quad (B.1)$$

where  $N$  is the number of cadavers (6),  $p$  is the number of predictors (2), and  $R$  is the unadjusted multiple correlation coefficient (Kim & Kohout, 1975). You can see that if  $p=1$  or  $N \gg p$ , then  $R' = R$ .

Note that for each of the segment masses, the adjusted coefficient was substantially better than the simple correlation coefficients of Chandler *et al.* (1975). Note, too, that the correlation coefficients for the moments of inertia equations proposed in the current method were in all cases (except one) markedly higher than those of Chandler. In that one case (the moment of inertia of the thigh

Table B.4 Comparison of Methods Used to Predict Body Segment Parameters for 6 Cadavers of Chandler *et al.* (1975)

Parameter	Segment	Chandler's method	GaitLab method	
		Correlation Coefficient	Correlation Coefficient	Adjusted Coefficient*
Mass	Thigh	0.941	0.998	0.997
	Calf	0.917	0.997	0.996
	Foot	0.784	0.899	0.872
Moment of inertia	Thigh			
	FbExt	0.865	0.901	
	AbdAdd	0.939	0.913	
	IntExt	0.876	0.932	
	Calf			
	FbExt	0.850	0.972	
	AbdAdd	0.821	0.962	
	IntExt	0.795	0.896	
	Foot			
	FbExt	0.696	0.899	
	AbdAdd	0.762	0.871	
	IntExt	0.819	0.825	

\*The correlation coefficients for the *GaitLab* method have to be adjusted for shrinkage because the equations to predict segment mass are based on more than one composite parameter. Refer to text for more detail.

about the abduction/adduction axis), our coefficient of 0.913 is still quite acceptable. It was not necessary to calculate an adjusted correlation coefficient for our moments of inertia, because only one predictor—a composite parameter having the dimension kilogram • metre • metre (kg•m<sup>2</sup>)—was used.

We believe that the evidence contained in Table B.4 provides encouraging support for our suggestion that the equations in Tables B.2 and B.3 are of benefit to the gait analyst, who can use these equations to personalise the BSPs of a subject knowing that they work extremely well with the original data from subjects whose sizes and shapes may be quite different from those of the 6 male cadavers of Chandler *et al.* (1975). The equations can be used on children or women or tall basketball players without giving unreasonable answers. The same cannot be said for regression equations, such as those proposed by Hinrichs (1985), that are not dimensionally consistent. This important issue has been addressed by Yeadon and Morlock (1989).

### Linear Kinematics

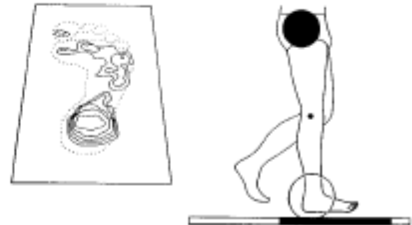
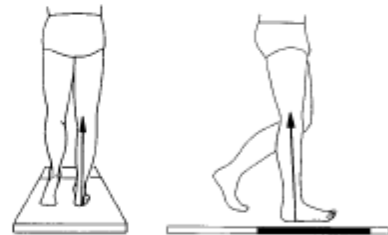
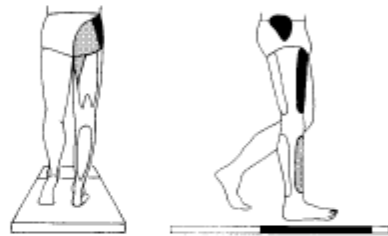
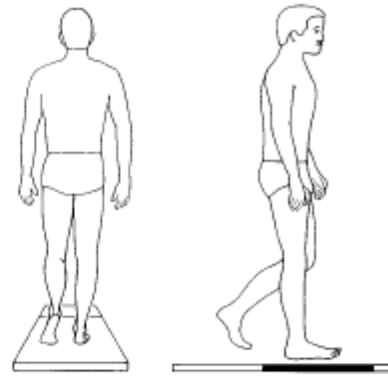
In this section we show how the 15 marker positions (see Figure 3.4 and Table B.5) may be used to accomplish two primary tasks. The first is to calculate *uvw* reference systems for each segment (see Figures 3.6 to 3.8) to predict the positions of joint centres and segment endpoints (see Equations 3.13 to 3.16). The second task is to use the joint centre positions and the external marker positions (Table B.5) to generate segment reference frames (*xyz*), which are embedded at the centres of gravity of each segment (see Figure 3.10).

Table B.5 Position Numbers and Names of External Marker Positions

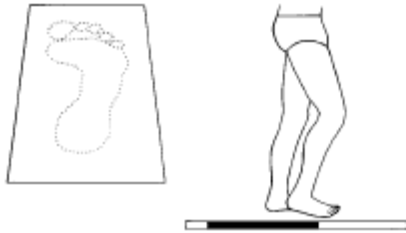
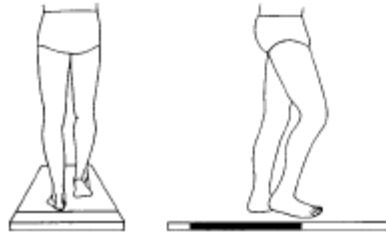
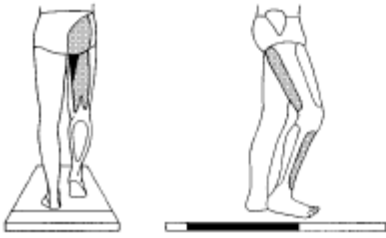
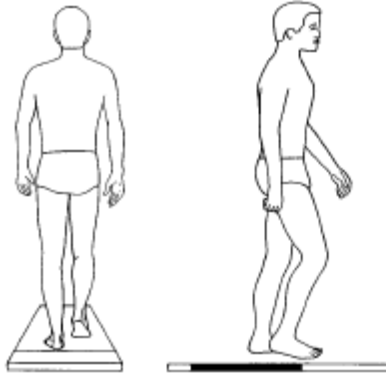
Position number	Name
P <sub>1</sub>	Right metatarsal head II
P <sub>2</sub>	Right heel
P <sub>3</sub>	Right lateral malleolus
P <sub>4</sub>	Right tibial wand
P <sub>5</sub>	Right femoral epiconyle
P <sub>6</sub>	Right femoral wand
P <sub>7</sub>	Right anterior superior iliac spine
P <sub>8</sub>	Left metatarsal head II
P <sub>9</sub>	Left heel
P <sub>10</sub>	Left lateral malleolus
P <sub>11</sub>	Left tibial wand
P <sub>12</sub>	Left femoral epiconyle
P <sub>13</sub>	Left femoral wand
P <sub>14</sub>	Left anterior superior iliac spine
P <sub>15</sub>	Sacrum

From Figure 3.6, we may define the unit vector triad *uvw* for the right foot as follows:

$$\mathbf{u}_{R, \text{Foot}} = (\mathbf{p}_1 - \mathbf{p}_2) / |\mathbf{p}_1 - \mathbf{p}_2| \quad (\text{B.2})$$

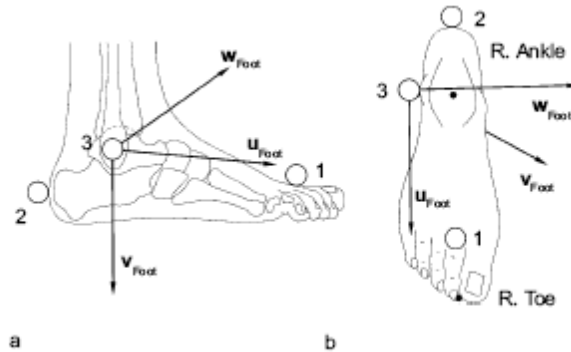


Frame = 6  
Time = 0.20 s



Frame = 23  
Time = 0.88 s

**Figure 3.6** The three markers (1, 2, and 3) which define the position of the foot in 3-D space: (a) side view; (b) view from above. The  $uvw$  reference system may be used to predict the position of the ankle and toe.



$$\mathbf{w}_{R, \text{Foot}} = \frac{(\mathbf{p}_1 - \mathbf{p}_3) \times (\mathbf{p}_2 - \mathbf{p}_3)}{|(\mathbf{p}_1 - \mathbf{p}_3) \times (\mathbf{p}_2 - \mathbf{p}_3)|} \quad (\text{B.3})$$

$$\mathbf{v}_{R, \text{Foot}} = \mathbf{w}_{R, \text{Foot}} \times \mathbf{u}_{R, \text{Foot}} \quad (\text{B.4})$$

Then, based on stereo X-rays (Vaughan, 1983), we have the following equations:

$$\mathbf{p}_{R, \text{Ankle}} = \mathbf{p}_3 + 0.016A_{13} \mathbf{u}_{R, \text{Foot}} + 0.392A_{15} \mathbf{v}_{R, \text{Foot}} + 0.478A_{17} \mathbf{w}_{R, \text{Foot}} \quad (\text{B.5})$$

and

$$\mathbf{p}_{R, \text{Toe}} = \mathbf{p}_3 + 0.742A_{13} \mathbf{u}_{R, \text{Foot}} + 1.074A_{15} \mathbf{v}_{R, \text{Foot}} + 0.187A_{19} \mathbf{w}_{R, \text{Foot}} \quad (\text{B.6})$$

which are the same as Equations 3.13 and 3.14. Similarly, we may calculate the unit vector triad  $uvw$  for the left foot as follows:

$$\mathbf{u}_{L, \text{Foot}} = (\mathbf{p}_8 - \mathbf{p}_9) / |\mathbf{p}_8 - \mathbf{p}_9| \quad (\text{B.7})$$

$$\mathbf{w}_{L, \text{Foot}} = \frac{(\mathbf{p}_8 - \mathbf{p}_{10}) \times (\mathbf{p}_9 - \mathbf{p}_{10})}{|(\mathbf{p}_8 - \mathbf{p}_{10}) \times (\mathbf{p}_9 - \mathbf{p}_{10})|} \quad (\text{B.8})$$

$$\mathbf{v}_{L, \text{Foot}} = \mathbf{w}_{L, \text{Foot}} \times \mathbf{u}_{L, \text{Foot}} \quad (\text{B.9})$$

As before, this unit vector triad may be used to estimate the following:

$$\mathbf{p}_{L, \text{Ankle}} = \mathbf{p}_{10} + 0.016A_{14} \mathbf{u}_{L, \text{Foot}} + 0.392A_{16} \mathbf{v}_{L, \text{Foot}} - 0.478A_{18} \mathbf{w}_{L, \text{Foot}} \quad (\text{B.10})$$

and

$$\mathbf{p}_{L, \text{Toe}} = \mathbf{p}_{10} + 0.742A_{14} \mathbf{u}_{L, \text{Foot}} + 1.074A_{16} \mathbf{v}_{L, \text{Foot}} + 0.187A_{20} \mathbf{w}_{L, \text{Foot}} \quad (\text{B.11})$$

which are similar to Equations B.5 and B.6, the main difference being that  $\mathbf{w}_{R, \text{Foot}}$  points medially, whereas  $\mathbf{w}_{L, \text{Foot}}$  points laterally.

From Figure 3.7, we may define the unit vector triad  $uvw$  for the right calf as follows:

$$\mathbf{v}_{R, \text{Calf}} = (\mathbf{p}_3 - \mathbf{p}_5) / |\mathbf{p}_3 - \mathbf{p}_5| \quad (\text{B.12})$$

$$\mathbf{w}_{R, \text{Calf}} = \frac{(\mathbf{p}_4 - \mathbf{p}_5) \times (\mathbf{p}_3 - \mathbf{p}_5)}{|(\mathbf{p}_4 - \mathbf{p}_5) \times (\mathbf{p}_3 - \mathbf{p}_5)|} \quad (\text{B.13})$$



---

**Figure 3.7** The three markers (3, 4, and 5), which define the position of the calf in 3-D space. This is an anterior view. The **uvw** reference system may be used to predict the position of the knee joint.

---



$$\mathbf{u}_{R.Calf} = \mathbf{v}_{R.Calf} \times \mathbf{w}_{R.Calf} \quad (B.14)$$

We can now calculate the position of the right knee:

$$\mathbf{p}_{R.Knee} = \mathbf{p}_5 + 0.000A_{11}\mathbf{u}_{R.Calf} + 0.000A_{11}\mathbf{w}_{R.Calf} - 0.500A_{11}\mathbf{u}_{R.Calf} \quad (B.15)$$

which is the same as Equation 3.15. Similarly, we may calculate the unit vector triad  $\mathbf{uvw}$  for the left calf as follows:

$$\mathbf{v}_{L.Calf} = (\mathbf{p}_{10} - \mathbf{p}_{12})/|\mathbf{p}_{10} - \mathbf{p}_{12}| \quad (B.16)$$

$$\mathbf{w}_{Pelvis} = \frac{(\mathbf{p}_{11} - \mathbf{p}_{12}) \times (\mathbf{p}_{10} - \mathbf{p}_{12})}{|(\mathbf{p}_{11} - \mathbf{p}_{12}) \times (\mathbf{p}_{10} - \mathbf{p}_{12})|} \quad (B.17)$$

$$\mathbf{u}_{L.Calf} = \mathbf{v}_{L.Calf} \times \mathbf{w}_{L.Calf} \quad (B.18)$$

As before, this vector triad may be used to estimate the position of the left knee:

$$\mathbf{p}_{L.Knee} = \mathbf{p}_{12} + 0.000A_{12}\mathbf{w}_{L.Calf} + 0.000A_{12}\mathbf{v}_{L.Calf} - 0.500A_{12}\mathbf{u}_{L.Calf} \quad (B.19)$$

which is similar to Equation B.15, the main difference being that  $\mathbf{w}_{R.Calf}$  points medially, whereas  $\mathbf{w}_{L.Calf}$  points laterally.

From Figure 3.8, we may define the unit vector triad  $\mathbf{uvw}$  for the pelvis as follows:

$$\mathbf{v}_{Pelvis} = (\mathbf{p}_{14} - \mathbf{p}_7)/|\mathbf{p}_{14} - \mathbf{p}_7| \quad (B.20)$$

$$\mathbf{w}_{L.Calf} = \frac{(\mathbf{p}_7 - \mathbf{p}_{15}) \times (\mathbf{p}_{14} - \mathbf{p}_{15})}{|(\mathbf{p}_7 - \mathbf{p}_{15}) \times (\mathbf{p}_{14} - \mathbf{p}_{15})|} \quad (B.21)$$

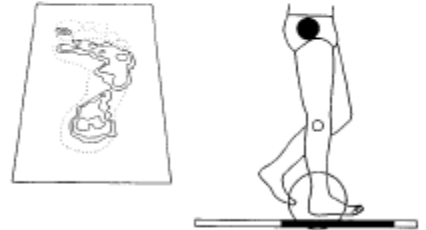
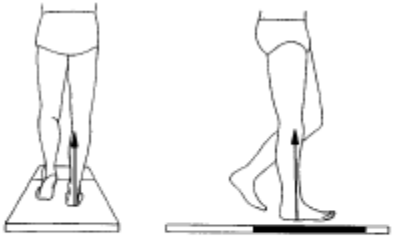
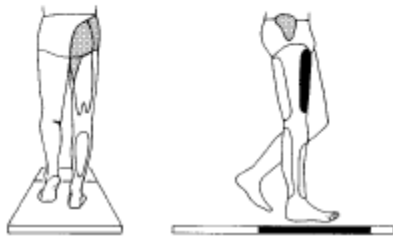
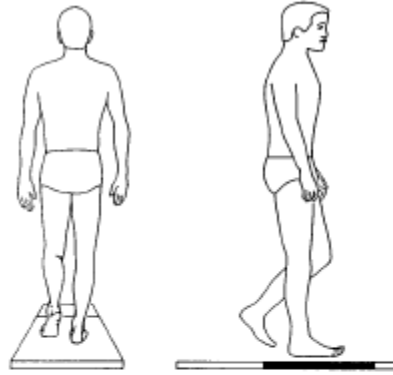
$$\mathbf{u}_{Pelvis} = \mathbf{v}_{Pelvis} \times \mathbf{w}_{Pelvis} \quad (B.22)$$

This same vector triad may be used to calculate the positions of both the right and left hips:

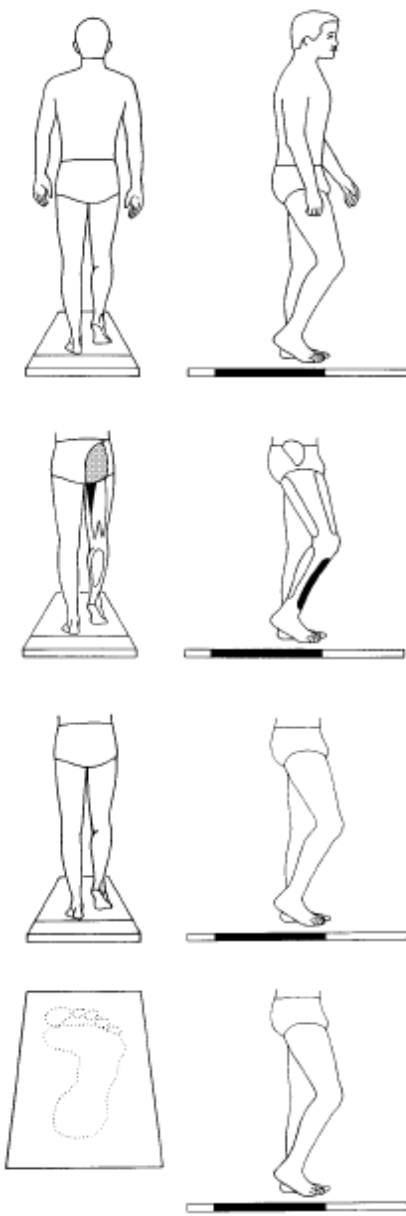
$$\mathbf{p}_{R.Hip} = \mathbf{p}_{15} + 0.598A_2\mathbf{u}_{Pelvis} - 0.344A_2\mathbf{v}_{Pelvis} - 0.290A_2\mathbf{w}_{Pelvis} \quad (B.23)$$

$$\mathbf{p}_{L.Hip} = \mathbf{p}_{15} + 0.598A_2\mathbf{u}_{Pelvis} + 0.344A_2\mathbf{v}_{Pelvis} - 0.290A_2\mathbf{w}_{Pelvis} \quad (B.24)$$

These equations (B.23 and B.24) for predicting the position of the hip joints are very similar to others in the literature (Campbell *et al.*, 1988; Tylkowski *et al.*, 1982).



Frame = 7  
Time = 0.24 s



Frame = 22  
Time = 0.84 s  
Right midswing

The next task is to use the joint centre positions and external marker positions to generate segment reference frames (xyz), which are embedded at the centres of gravity of each segment (see Figure 3.10). There are a few observations that need to be made first:

**IJK** are the unit vectors in the XYZ directions;

**ijk** are the unit vectors in the xyz directions.

$$\mathbf{i}_{\text{Pelvis}} = \mathbf{w}_{\text{Pelvis}}$$

$$\mathbf{j}_{\text{Pelvis}} = \mathbf{u}_{\text{Pelvis}}$$

$$\mathbf{k}_{\text{Pelvis}} = \mathbf{v}_{\text{Pelvis}}$$

Segment 1 is the Right Thigh;

Segment 2 is the Left Thigh;

Segment 3 is the Right Calf;

Segment 4 is the Left Calf;

Segment 5 is the Right Foot;

Segment 6 is the Left Foot.

The unit vector triad **ijk** defining the directions of xyz in the segments may be calculated as follows:

**Right Thigh**

$$\mathbf{i}_1 = \frac{(\mathbf{p}_{R.Hip} - \mathbf{p}_{R.Knee})}{|\mathbf{p}_{R.Hip} - \mathbf{p}_{R.Knee}|} \quad (\text{B.25})$$

$$\mathbf{j}_1 = \frac{(\mathbf{p}_6 - \mathbf{p}_{R.Hip}) \times (\mathbf{p}_{R.Knee} - \mathbf{p}_{R.Hip})}{|(\mathbf{p}_6 - \mathbf{p}_{R.Hip}) \times (\mathbf{p}_{R.Knee} - \mathbf{p}_{R.Hip})|} \quad (\text{B.26})$$

$$\mathbf{k}_1 = \mathbf{i}_1 \times \mathbf{j}_1 \quad (\text{B.27})$$

**Left Thigh**

$$\mathbf{i}_2 = \frac{(\mathbf{p}_{L.Hip} - \mathbf{p}_{L.Knee})}{|\mathbf{p}_{L.Hip} - \mathbf{p}_{L.Knee}|} \quad (\text{B.28})$$

$$\mathbf{j}_2 = \frac{(\mathbf{p}_{L.Knee} - \mathbf{p}_{L.Hip}) \times (\mathbf{p}_{L3} - \mathbf{p}_{L.Hip})}{|(\mathbf{p}_{L.Knee} - \mathbf{p}_{L.Hip}) \times (\mathbf{p}_{L3} - \mathbf{p}_{L.Hip})|} \quad (\text{B.29})$$

$$\mathbf{k}_2 = \mathbf{i}_2 \times \mathbf{j}_2 \quad (\text{B.30})$$

**Right Calf**

$$\mathbf{i}_3 = \frac{(\mathbf{p}_{R.Knee} - \mathbf{p}_{R.Ankle})}{|\mathbf{p}_{R.Knee} - \mathbf{p}_{R.Ankle}|} \quad (\text{B.31})$$

$$\mathbf{j}_3 = \frac{(\mathbf{p}_5 - \mathbf{p}_{R.Knee}) \times (\mathbf{p}_{R.Ankle} - \mathbf{p}_{R.Knee})}{|(\mathbf{p}_5 - \mathbf{p}_{R.Knee}) \times (\mathbf{p}_{R.Ankle} - \mathbf{p}_{R.Knee})|} \quad (\text{B.32})$$

$$\mathbf{k}_3 = \mathbf{i}_3 \times \mathbf{j}_3 \quad (\text{B.33})$$

#### Left Calf

$$i_4 = \frac{(p_{L.Knee} - p_{L.Ankle})}{|p_{L.Knee} - p_{L.Ankle}|} \quad (B.34)$$

$$j_4 = \frac{(p_{L.Ankle} - p_{L.Knee}) \times (p_{L2} - p_{L.Knee})}{|(p_{L.Ankle} - p_{L.Knee}) \times (p_{L2} - p_{L.Knee})|} \quad (B.35)$$

$$k_4 = i_4 \times j_4 \quad (B.36)$$

#### Right Foot

$$i_5 = \frac{(p_2 - p_{R.Toe})}{|p_2 - p_{R.Toe}|} \quad (B.37)$$

$$k_5 = \frac{(p_{R.Ankle} - p_2) \times (p_{R.Toe} - p_2)}{|(p_{R.Ankle} - p_2) \times (p_{R.Toe} - p_2)|} \quad (B.38)$$

$$j_5 = k_5 \times i_5 \quad (B.39)$$

#### Left Foot

$$i_6 = \frac{(p_9 - p_{L.Toe})}{|p_9 - p_{L.Toe}|} \quad (B.37)$$

$$k_6 = \frac{(p_{L.Ankle} - p_9) \times (p_{L.Toe} - p_9)}{|(p_{L.Ankle} - p_9) \times (p_{L.Toe} - p_9)|} \quad (B.38)$$

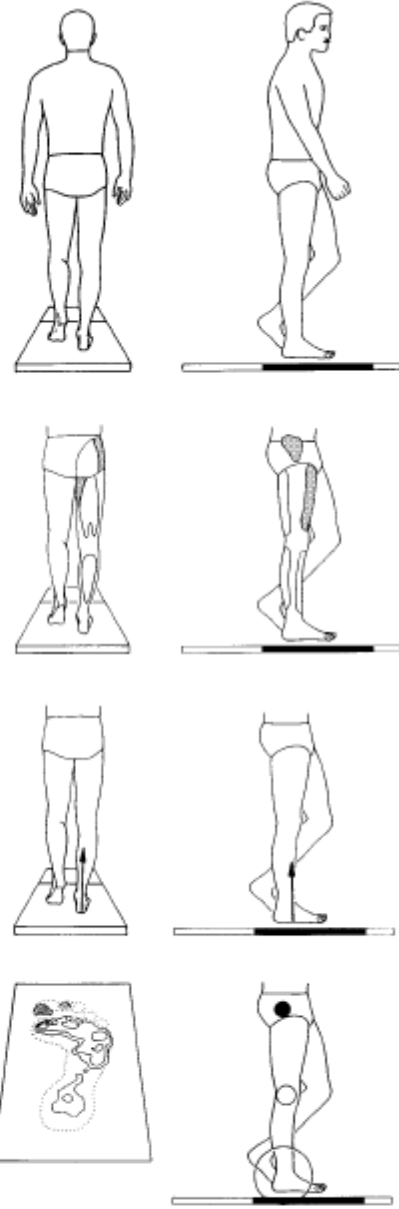
$$j_6 = k_6 \times i_6 \quad (B.42)$$

It is important to realise that although these *ijk* vector triads are used to define the segmental coordinate system *xyz*, they are actually expressed in terms of the global reference system *XYZ*. The *XYZ* coordinates for the *ijk* vector triad of the pelvis and the six lower extremity segments are listed for time = 0.00 s in Table B.6 (which contains the data for the Man.DST file used in *GaitLab*).

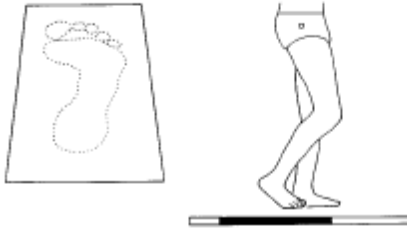
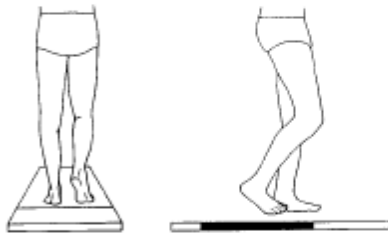
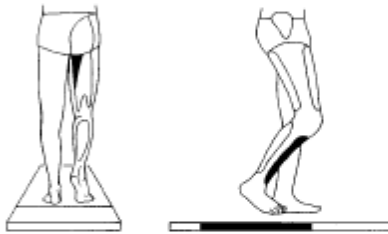
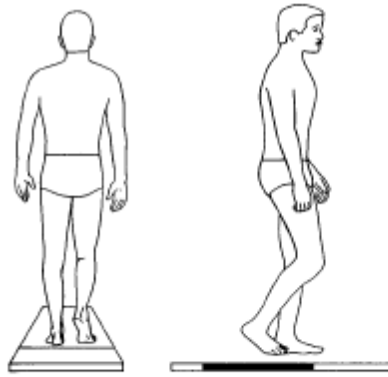
#### Centres of Gravity

This section has three purposes: First, we provide the equations that are used to estimate centres of gravity based on joint centres and segment endpoints; second, we discuss the digital filter that is used to smooth raw position data; and third, we cover the finite difference theory that is the basis for performing numerical differentiation to calculate velocities and accelerations.

From Figure 3.11 and Tables 3.5 and B.2, the following equations may be derived:



Frame = 8  
Time = 0.28 s  
Right midstance



Frame = 21  
Time = 0.80 s

$$p_{R.Thigh.CG} = p_{R.Hip} + 0.39 (p_{R.Knee} - p_{R.Hip}) \quad (B.43)$$

$$p_{L.Thigh.CG} = p_{L.Hip} + 0.39 (p_{L.Knee} - p_{L.Hip}) \quad (B.44)$$

$$p_{R.Calf.CG} = p_{R.Knee} + 0.42 (p_{R.Ankle} - p_{R.Knee}) \quad (B.45)$$

$$p_{L.Calf.CG} = p_{L.Knee} + 0.42 (p_{L.Ankle} - p_{L.Knee}) \quad (B.46)$$

$$p_{R.Foot.CG} = p_{R.Heel} + 0.44 (p_{R.Toe} - p_{R.Heel}) \quad (B.47)$$

$$p_{L.Foot.CG} = p_{L.Heel} + 0.44 (p_{L.Toe} - p_{L.Heel}) \quad (B.48)$$

In human movement activities such as gait, the frequency of the displacement signal is almost always less than the frequency of the noise. The purpose of a digital filter, therefore, is to filter out the high-frequency noise while allowing the low-frequency displacement signal to pass through untouched. The format of a low-pass digital filter is as follows:

$$x'_n = a_0 x_n + a_1 x_{n-1} + a_2 x_{n-2} + b_1 x'_{n-1} + b_2 x'_{n-2} \quad (B.49)$$

where  $x'$  refers to filtered output coordinates,  $x$  refers to raw unfiltered coordinate data,  $n$  refers to the  $n$ th sample frame, and  $a_0$  through  $b_2$  are the filter coefficients. These filter coefficients are constants that depend on the type and order of the filter, the sampling frequency (*i.e.*, the frame rate), and the cutoff frequency (*i.e.*, how much noise should be attenuated). As can be seen from Equation B.49, the filtered output  $x'_n$  is a weighted version of the immediate and past raw data, plus a weighted contribution of past filtered output. For the *GaitLab* program, the second-order low-pass Butterworth filter was used. Further details may be obtained in Radar and Gold (1967) and Winter (1979). A FORTRAN listing of the subroutine DIGFIL which implements Equation A.49 may be found in Vaughan (1982).

We pointed out in chapter 3 that the digital filter has endpoint problems, which can lead to erroneous velocities and accelerations in the first few and last few frames. One of the algorithms that does

Table B.6 Three-Dimensional Coordinates of the  $ijk$  Unit Vectors for Segment Reference Frames at Time = 0.00 s (Right Heel Strike) for a Normal Male

Segment	$i_x$	$i_y$	$i_z$
Pelvis	-0.072	0.017	0.997
R. Thigh	-0.385	-0.088	0.919
L. Thigh	0.305	-0.001	0.952
R. Calf	-0.213	-0.016	0.977
L. Calf	0.606	0.001	0.795
R. Foot	-0.936	-0.095	-0.339
L. Foot	-0.884	0.043	0.465

Segment	$j_x$	$j_y$	$j_z$
Pelvis	0.996	0.053	0.071
R. Thigh	0.922	-0.008	0.386
L. Thigh	0.917	0.272	-0.293
R. Calf	0.977	-0.022	0.212
L. Calf	0.791	0.103	-0.603
R. Foot	-0.298	-0.302	0.906
L. Foot	0.454	0.309	0.835

Segment	$k_x$	$k_y$	$k_z$
Pelvis	-0.052	0.998	-0.021
R. Thigh	-0.026	0.996	0.084
L. Thigh	-0.258	0.962	0.084
R. Calf	0.018	1.000	0.021
L. Calf	-0.083	0.995	0.062
R. Foot	-0.188	0.949	0.254
L. Foot	-0.108	0.950	-0.294

Note. The XYZ values refer to the global coordinate system defined in Figure 3.10.

not have these endpoint problems is the quintic spline (Vaughan, 1982; Wood & Jennings, 1979). We had planned to offer the quintic spline as an option for smoothing and differentiating in the *GaitLab* software, but the size of the code and its running time precluded this option.

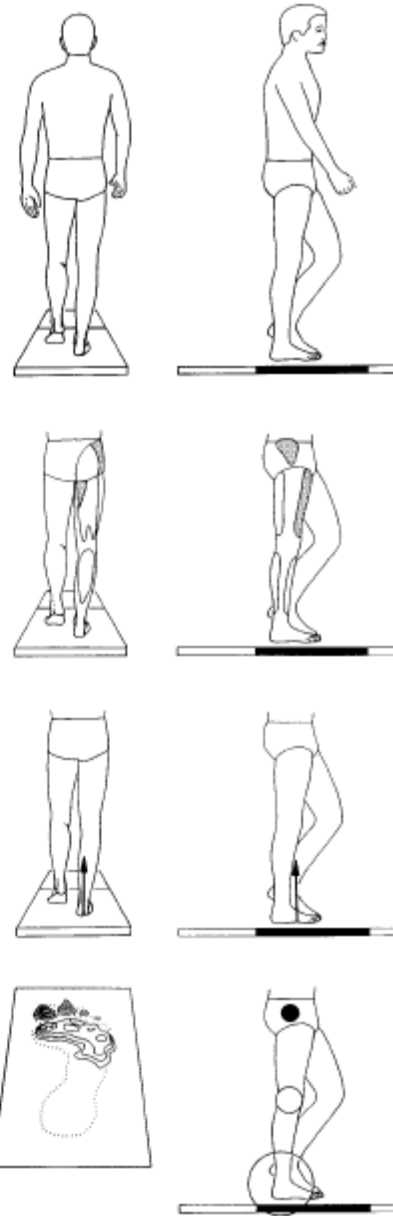
We have based our method for determining numerical differentiation on finite difference theory. Finite difference methods may be derived from Taylor series expansions (Miller & Nelson, 1973), and they provide formulae for calculating first and second derivatives of displacement-time data. The first and second derivatives (i.e., velocity and acceleration) are expressible as

$$\frac{dx_n}{dt} = \dot{x}_n = \frac{x_{n+1} - x_{n-1}}{2\Delta t} \quad (\text{B.50})$$

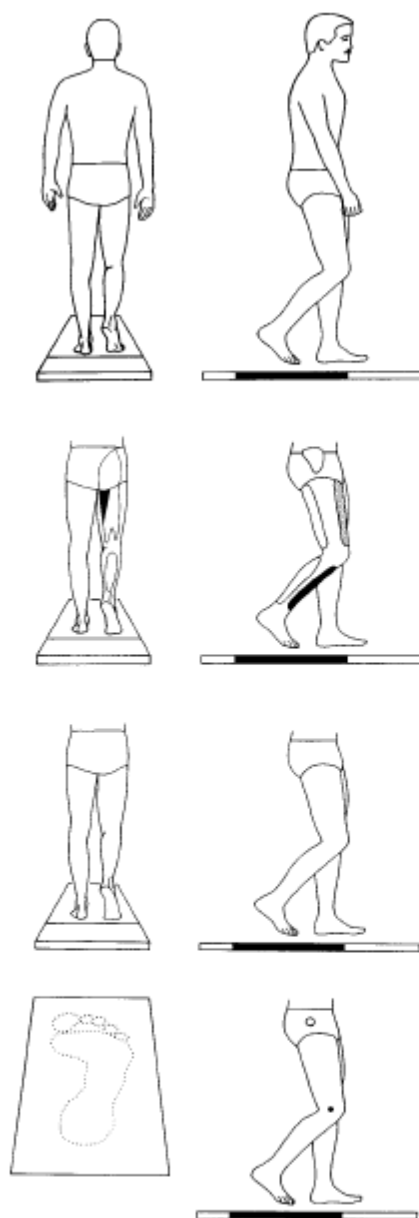
and

$$\frac{d^2x_n}{dt^2} = \ddot{x}_n = \frac{x_{n+1} - 2x_n + x_{n-1}}{(\Delta t)^2} \quad (\text{B.51})$$

where  $x$  is an input data point,  $n$  refers to the  $n$ th sample frame, and  $\Delta t$  is the time between adjacent frames. Equations B.50 and B.51 are known as central difference formulae. Forward and backward difference formulae may be used for derivatives of displacement data at the beginning and end of the data set. All these formulae are approximations, because the time interval  $\Delta t$  is not infinitely small. Therefore, any noise in the input signal has a large influence on the accuracy of the derivative values. A FORTRAN listing of the subroutine FIDIFF which implements Equations B.50 and B.51 is also included in the paper by Vaughan (1982).



Frame = 9  
Time = 0.32 s



Frame = 20  
Time = 0.76 s  
Right acceleration

## Angular Kinematics

In this section we will cover three areas: definition of anatomical joint angles, definition of segment Euler angles, and derivation of segment angular velocities and accelerations based on the Euler angles.

We stated in chapter 3 that we chose to adopt the methods proposed by Chao (1980) and Grood and Suntay (1983) for defining our anatomical joint angles. Consider the segment reference frames defined in Figure 3.10. The lower extremities have been partitioned into six pairs of segments in Figure B.1, a-f.

The following conventions apply to all six joints:

$k_{\text{Proximal}}$  = flexion/extension axis.

$i_{\text{Distal}}$  = internal/external rotation axis.

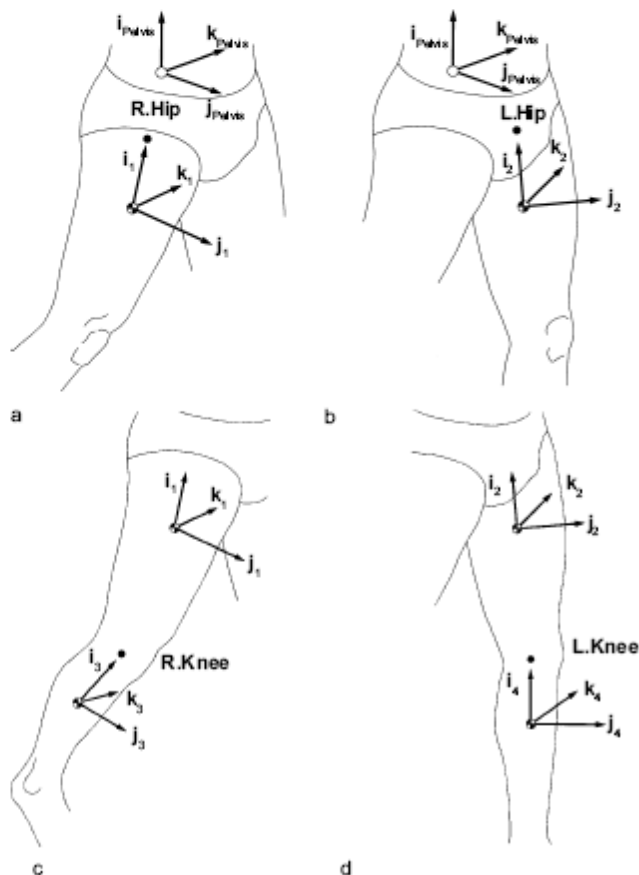
$i_{\text{Joint}}$  = abduction/adduction axis.

$$I_{\text{Joint}} = \frac{k_{\text{Proximal}} \times i_{\text{Distal}}}{|k_{\text{Proximal}} \times i_{\text{Distal}}|} \quad (\text{B.52})$$

$\alpha$  = flexion/extension angle.

$\beta$  = abduction/adduction angle.

$\gamma$  = internal/external rotation angle.



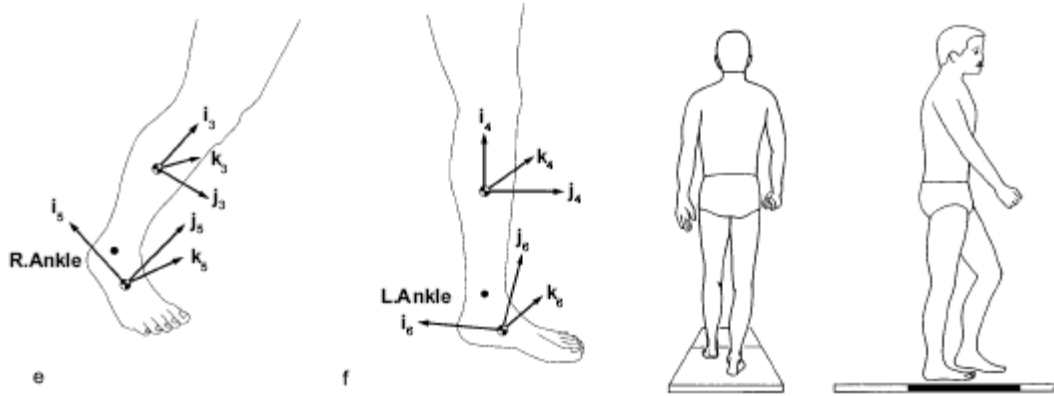


Figure B.1 Unit vector reference frames embedded in the proximal and distal segments on either side of an anatomical joint: (a) right hip; (b) left hip; (c) right knee; (d) left knee; (e) right ankle; (f) left ankle.

Flexion is positive and extension is negative.  
Abduction is positive and adduction is negative.  
Internal rotation is positive and external rotation is negative.

Using these conventions and the unit vector triads in Figure B.1, we get the following relationships for the anatomical joint angles:

$$\alpha_{R.Hip} = \sin^{-1}[\mathbf{l}_{R.Hip} \cdot \mathbf{i}_{Pelvis}] \quad (B.53)$$

$$\beta_{R.Hip} = \sin^{-1}[\mathbf{k}_{Pelvis} \cdot \mathbf{i}_1] \quad (B.54)$$

$$\gamma_{R.Hip} = \sin^{-1}[\mathbf{l}_{R.Hip} \cdot \mathbf{k}_1] \quad (B.55)$$

$$\alpha_{L.Hip} = \sin^{-1}[\mathbf{l}_{L.Hip} \cdot \mathbf{i}_{Pelvis}] \quad (B.56)$$

$$\beta_{L.Hip} = \sin^{-1}[\mathbf{k}_{Pelvis} \cdot \mathbf{i}_2] \quad (B.57)$$

$$\gamma_{L.Hip} = \sin^{-1}[\mathbf{l}_{L.Hip} \cdot \mathbf{k}_2] \quad (B.58)$$

$$\alpha_{R.Knee} = \sin^{-1}[\mathbf{l}_{R.Knee} \cdot \mathbf{i}_1] \quad (B.59)$$

$$\beta_{R.Knee} = \sin^{-1}[\mathbf{k}_1 \cdot \mathbf{i}_3] \quad (B.60)$$

$$\gamma_{R.Knee} = \sin^{-1}[\mathbf{l}_{R.Knee} \cdot \mathbf{k}_3] \quad (B.61)$$

$$\alpha_{L.Knee} = \sin^{-1}[\mathbf{l}_{L.Knee} \cdot \mathbf{i}_2] \quad (B.62)$$

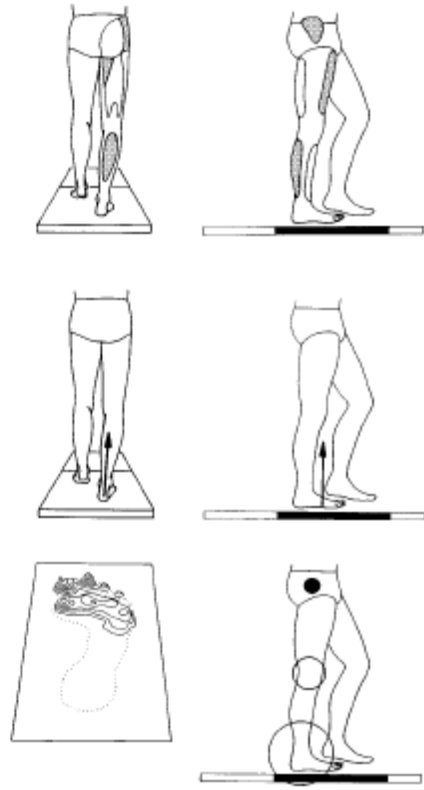
$$\beta_{L.Knee} = \sin^{-1}[\mathbf{k}_2 \cdot \mathbf{i}_4] \quad (B.63)$$

$$\gamma_{L.Knee} = \sin^{-1}[\mathbf{l}_{L.Knee} \cdot \mathbf{k}_4] \quad (B.64)$$

$$\alpha_{R.Ankle} = \sin^{-1}[\mathbf{l}_{R.Ankle} \cdot \mathbf{j}_3] \quad (B.65)$$

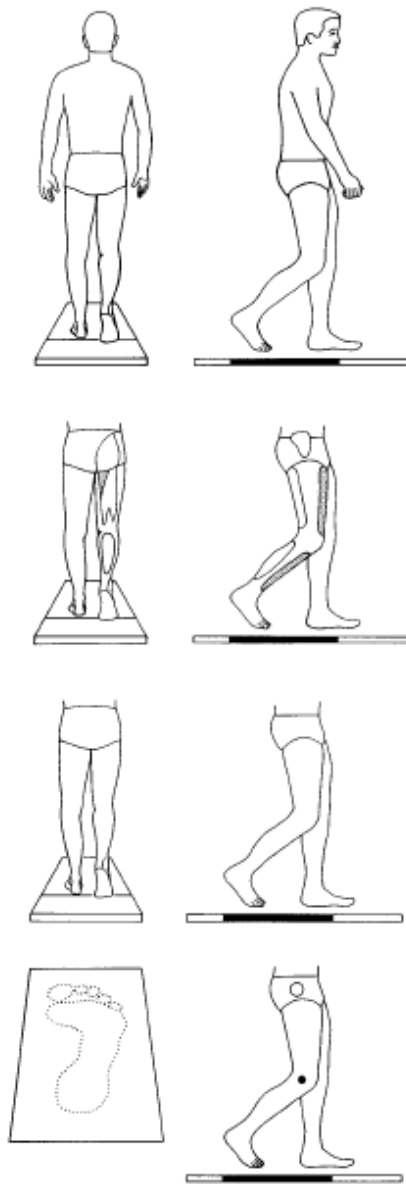
$$\beta_{R.Ankle} = \sin^{-1}[\mathbf{k}_3 \cdot \mathbf{i}_5] \quad (B.66)$$

$$\gamma_{R.Ankle} = \sin^{-1}[\mathbf{l}_{R.Ankle} \cdot \mathbf{k}_5] \quad (B.67)$$



Frame=10  
Time = 0.36 s





Frame = 19  
Time = 0.72 s

$$\alpha_{L,Ankle} = \sin^{-1}[\mathbf{l}_{L,Ankle} \cdot \mathbf{j}_d] \quad (B.68)$$

$$\beta_{L,Ankle} = -\sin^{-1}[\mathbf{k}_d \cdot \mathbf{i}_s] \quad (B.69)$$

$$\gamma_{L,Ankle} = \sin^{-1}[\mathbf{l}_{L,Ankle} \cdot \mathbf{k}_s] \quad (B.70)$$

Note that for the angles at the left and right ankle joints, the following conventions apply:

- $\alpha$  = plantar flexion (positive) and dorsiflexion (negative)
- $\beta$  = varus (positive) and valgus (negative)
- $\gamma$  = inversion (positive) and eversion (negative)

The neutral position for determining plantar flexion and dorsiflexion is a right angle between the long axes of the calf and foot.

We showed in chapter 3 that a segment reference frame  $xyz$  may be orientated in 3-D space relative to the global reference system  $XYZ$  by means of three Euler angles. The Euler angle rotations are performed in the following order:

- (a)  $\phi$  about the  $\mathbf{K}$  axis of the global reference frame,
- (b)  $\theta$  about the line of nodes, and
- (c)  $\psi$  about the  $\mathbf{k}$  axis of the segment,

where the line of nodes is a unit vector defined as

$$\mathbf{L} = \frac{(\mathbf{K} \times \mathbf{k})}{|\mathbf{K} \times \mathbf{k}|} \quad (B.71)$$

By way of example, Figure 3.16 has been expanded into Figure B.2, a-c, which shows each of the Euler angles for a single segment. The angles may be calculated as follows:

$$\phi = \sin^{-1}[(\mathbf{I} \times \mathbf{L}) \cdot \mathbf{K}] \quad (B.72)$$

$$\theta = \sin^{-1}[(\mathbf{K} \times \mathbf{k}) \cdot \mathbf{L}] \quad (B.73)$$

$$\psi = \sin^{-1}[(\mathbf{L} \times \mathbf{i}) \cdot \mathbf{k}] \quad (B.74)$$

Our convention for the definition of the Euler angles is based on two classical mechanics texts by Synge and Griffith (1959) and Goldstein (1965). The segment angular velocities may be obtained from the Euler angles as follows:

$$\dot{\omega}_{segment,x} = \dot{\phi} \sin \theta \sin \psi + \dot{\theta} \cos \psi \quad (B.75)$$

$$\dot{\omega}_{segment,y} = \dot{\phi} \sin \theta \cos \psi - \dot{\theta} \sin \psi \quad (B.76)$$

$$\dot{\omega}_{segment,z} = \dot{\phi} \cos \theta + \dot{\psi} \quad (B.77)$$

where the segment angular velocities  $\omega$  are given relative to the segment-based reference frame  $xyz$ , and the dot above the Euler angles

(e.g.,  $\dot{\phi}$ ) indicates the first derivative with respect to time (e.g.,  $\frac{d\phi}{dt}$ ).

By taking the first derivative of Equations B.75 to B.77, we get the segment angular accelerations:

$$\dot{\omega}_{segment,x} = \ddot{\phi}\sin\theta\sin\psi + \ddot{\theta}\cos\theta\sin\psi + \ddot{\psi}\sin\theta\cos\psi + \ddot{\theta}\cos\psi - \dot{\theta}\dot{\psi}\sin\psi \quad (B.78)$$

$$\dot{\omega}_{segment,y} = \ddot{\phi}\sin\theta\cos\psi + \ddot{\theta}\cos\theta\cos\psi + \ddot{\psi}\sin\theta\sin\psi - \dot{\theta}\sin\psi - \dot{\theta}\dot{\psi}\cos\psi \quad (B.79)$$

$$\dot{\omega}_{segment,z} = \ddot{\phi}\cos\theta - \ddot{\theta}\sin\theta + \ddot{\psi} \quad (B.80)$$

The Euler angles  $\phi\theta\psi$  are smoothed using the digital filter described earlier in this chapter (Equation B.49), whereas finite difference methods (Equations B.50 and B.51) may be used to calculate first and second derivatives.

### Dynamics of Joints

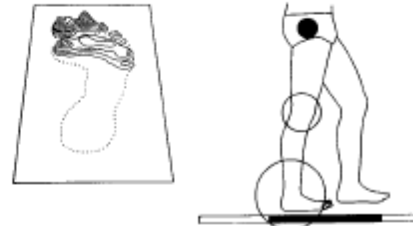
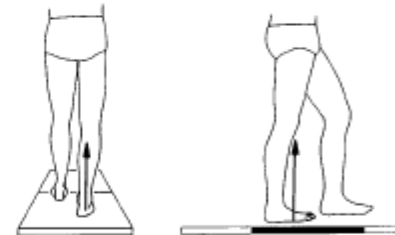
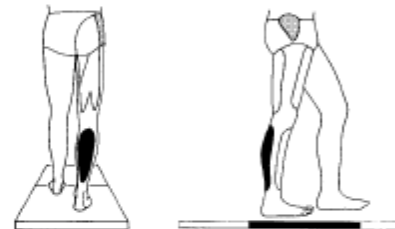
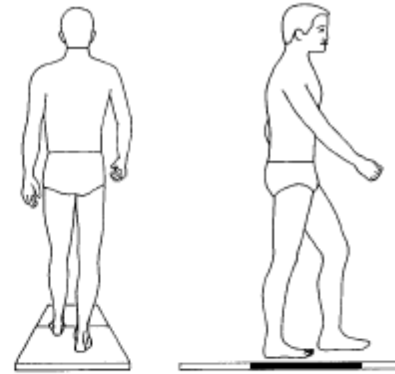
We are now at the stage where we can integrate all the previous sections and, using Newton's second and third laws of motion, generate the resultant forces and moments acting at the lower extremity joints. In fact, we will integrate the following:

- Body segment parameters (BSP data)
- Segment centres of gravity, velocities, and accelerations (COG data)
- Ground reactions from force plates (FPL data)
- Joint centres and segment endpoints (JNT data)
- Segment reference frames (REF data)
- Segment angular velocities and accelerations (ANG data)

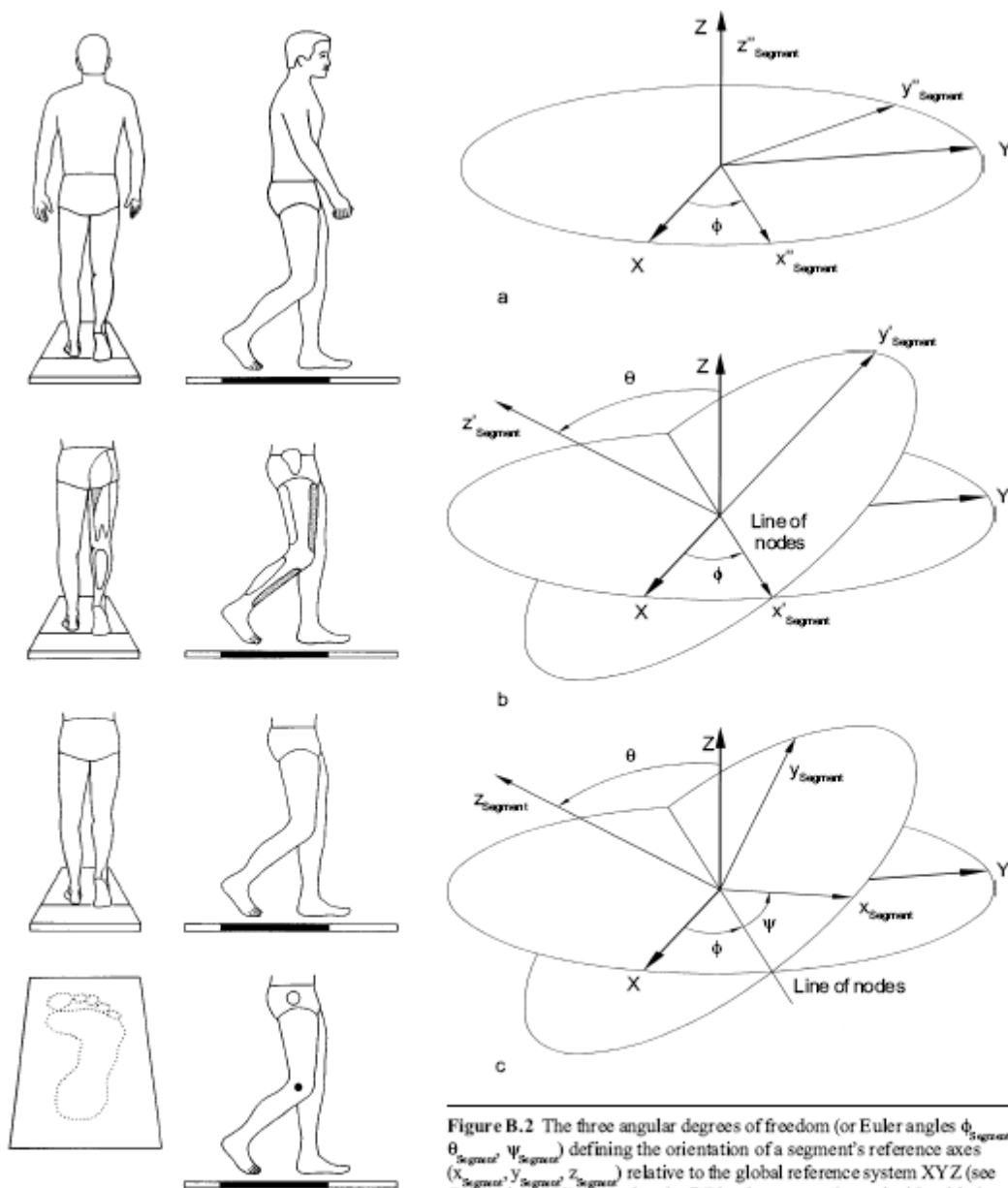
In performing this integration, we will follow a standard procedure of six steps for each of the segments:

1. Calculate the forces at the proximal joint using the linear form of Newton's second law.
2. Calculate the moment arms, proximal and distal, between the force application point and the segment centre of gravity.
3. Calculate the residual moment acting on the segment.
4. Calculate the rate of change of angular momentum for the segment.
5. Calculate the resultant joint moment, first in the xyz system using the angular form of Newton's second law, then in the XYZ system.
6. Convert the joint force and moment from the XYZ system to a body-based system.

It is also pertinent to point out that these six steps are performed first on the foot, then on the calf, and finally on the thigh.



Frame = 11  
Time = 0.40 s



Frame = 18  
Time = 0.68 s

Figure B.2 The three angular degrees of freedom (or Euler angles  $\phi_{Segment}$ ,  $\theta_{Segment}$ ,  $\psi_{Segment}$ ) defining the orientation of a segment's reference axes ( $X_{Segment}$ ,  $Y_{Segment}$ ,  $Z_{Segment}$ ) relative to the global reference system XYZ (see Goldstein, 1965). Note that the CG has been moved to coincide with the origin of XYZ. The three Euler angle rotations take place in the following order: (a)  $\phi_{Segment}$  about the Z axis; (b)  $\theta_{Segment}$  about the line of nodes; and (c)  $\psi_{Segment}$  about the  $z_{Segment}$  axis. The line of nodes is perpendicular to both the Z and  $z_{Segment}$  axes. The primes and double primes indicate the intermediate axis positions.

## APPENDIX C : RECRUITMENT AND TESTING MATERIALS

*Health Screen- Healthy Controls*

Phone #:

Address:

Subject Identification Number:

Date of Screen:

Subject name: \_\_\_\_\_  
Last First

“My name is \_\_\_\_\_. I am calling from the Biodynamics Laboratory at the University of Kansas. I was given your name as someone who had indicated an interest in participating in a research study. We are now beginning a study looking at how the brain controls our balance and how that might be related to risk of falling. If you think you might be interested in participating, and you have a few minutes, I’d like to describe the study to you.”

Is subject interested? YES NO

Comments: \_\_\_\_\_  
\_\_\_\_\_

If NO: “Thank you for your time. Would you be interested in being contacted for future studies or do you prefer that your name is removed from our list?”

Comments: \_\_\_\_\_  
\_\_\_\_\_

If YES: “Please feel free to ask questions at any time. This study is a one-time evaluation that will look at how Parkinson’s disease affects the ability of the brain to control our balance. We will be looking at those with Parkinson’s compared to healthy adults in the same age range. There are two parts to this study. First, there is a medical screening procedure. The first part is done over the phone and will take approximately 20 minutes. This will include questions about current and previous health conditions. Once that is completed we will schedule you for a visit to the Biodynamics Laboratory at KU in Lawrence where we will do a physical assessment that and then do the balance testing. For the balance testing, we will ask you to do four different tests: one that just involves standing still, one that involves starting to walk from rest, one that involves walking on a treadmill for about 5 minutes, and a balance recovery test. For the balance recovery test, we will pull you backwards from the waist and you will have to regain your balance. During all of the tests, you will be wearing a protective harness to ensure your safety. The whole test will take approximately 3 hours. There is no cost for participating in this study, nor are there any direct benefits to you. We will pay you \$30 for your participation. If you are still interested, I would like to ask you some questions to see if you would be able to participate in this study.”

Notes: \_\_\_\_\_  
\_\_\_\_\_

\*\*If subject is excluded by any questions, stop the interview and explain to the subject the reason for exclusion. Thank them for their time and willingness to participate.

Name: \_\_\_\_\_ Age: \_\_\_\_\_  
Birthdate: \_\_\_\_\_  
Gender: M F  
Address: \_\_\_\_\_

Phone: \_\_\_\_\_

Schooling/Occupation: \_\_\_\_\_

Height: \_\_\_\_\_ Weight: \_\_\_\_\_

Are you currently participating in any other research studies?

This study will require one trip to the University of Kansas in Lawrence. Would you have transportation for this visit?

Are you able to get out of bed and also use the bathroom without assistance from anything or anyone?

Are you able to stand on your own for 10 minutes without assistance?  
(ex. Can you stand at the bathroom sink to do your morning care without having to hold to something?)

#### SUMMARY OF MEDICAL SCREEN:

Pass? If no, why not?

Height: \_\_\_\_\_ Weight: \_\_\_\_\_ Age: \_\_\_\_\_ Gender: \_\_\_\_\_

Comments:

Have you been diagnosed with:	Yes	No	When	Details	Exclude?
Ever had major surgery or amputation?					Yes if affects legs, not recovered completely
Osteoporosis					Yes
Brittle Bones					Yes
Fibromyalgia? Constant aches and fatigue?					Yes if constant
Arthritis					Yes if in legs
Nerve Damage					Yes if in legs
Heart Attack					Yes
Heart Disease or problems (surgeries, valve replacement, angina, pacemaker?)					Yes
Chest Pain from heart disease?					Yes
Polio or Post Polio Syndrome					Yes
Broken Bones? Compression fractures?					Yes if < 2 years ago and in leg or spine
Ever had a hip, knee, or ankle replacement or surgery?					Yes
Ever had a joint fusion?					Yes
Diabetes? Thyroid conditions?					Yes if not controlled or if have neuropathy
High Blood Pressure					Yes if not controlled on meds
Neurological Disease (MS, ALS, Dementia, Seizure disorders, PD)					Yes
Stroke or TIA					Yes
Cancer, Leukemia, Lymphoma?					Yes if currently being treated
Anemia					Yes if has had blood transfusion in last year
Seizure					Yes
Meniere's Disease? Inner Ear Damage? Vertigo? Ear infection now?					Yes
Acoustic Neuroma? Tinnitus? (ringing, buzzing in ears) Do you feel pressure in ears?					Yes if constant
Do you have any problems with:	Yes	No	How does it affect ADL?		Exclude?

Pain or stiffness in hips? Knee? Ankles? Back? Shoulder?				Yes if affects walking, standing
Hip, Knee, or Ankle injury?				Yes if affects walking, standing
Back Problems? If yes: What motions cause pain (bending, twisting, lifting, quick movements?) How irritable is the pain? How do you treat the pain? Have you seen a doctor?				Yes if brought on by walking, standing, quick movements, if brought on easily
Muscle Problems in leg? Weakness in legs? Does it limit how far you can walk or how long you can stand?				Yes if affects walking, standing
Poor circulation in legs causing them to become cold, numb, or causes cramping while walking, been diagnosed with PVD? Claudication?				Only if causes problems when walking or standing
Lung disease? Emphezema? Chronic Bronchitis? SOB? DOE?				Yes if affects walking, standing
Ever had a head or neck injury?				Not necessarily
Gout or Psuedogout?				Not necessarily
Foot problems?				Not necessarily
Hearing Problems? Hearing aid? Last hearing exam?				Not necessarily
Have you been hospitalized in the past year? Major illness in last year?				Not necessarily
Headaches				Not necessarily
Neuropathy				Not necessarily
Vision				Not necessarily
Falls				Not necessarily
Driving				Not necessarily
Night Driving				Not necessarily
Shortness of Breath				Not necessarily
Edema (swelling of legs)				Not necessarily
Fainting or lightheadedness?				Not necessarily
Memory				Not necessarily



Burning pain or weakness anywhere				Not necessarily
Depression				Not necessarily

#### MEDICATIONS:

What medications are you currently taking?

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

OTC Medications:

#### ACTIVITY:

Are you able to leave house / apartment on your own? How often?

\_\_\_\_\_

When you walk, do you walk with : Self walker/cane person assist unable

How far do you walk on a daily basis? \_\_\_\_\_

How often do you walk? \_\_\_\_\_

How long do you walk (duration) \_\_\_\_\_

Do you participate in any exercise/Activities?

Type \_\_\_\_\_

Sessions per week \_\_\_\_\_

Minutes / hours per session \_\_\_\_\_

When you transfer from a sitting to standing position, do you do it:

Alone With assistive device With person assist Unable

When you transfer from lying down to sitting, do you do it:

Alone With assistive device With person assist Unable

Hand dominance L R

(Are you right or left-handed?)

Leg dominance L R

(Which leg would you kick a ball with?)

Recent vision screen? If yes, when?

BARTHEL INDEX: SEE FULL VERSION

	With Help	Independent
1. Feeding	5	10
2. Moving from wheelchair to bed and return	5-10	15
3. Personal toilet (wash face, comb hair, etc.)	0	5
4. Getting on and off toilet (handling clothes, flush, wipe)	5	10
5. Bathing self	0	5
6. Walking on level surface	10	15
7. Ascend and descend stairs	5	10
8. Dressing (includes tying shoes, fastening)	5	10
9. Controlling bowels	5	10
10. Controlling bladder	5	10

Is there anything else you can think of about your current or past health state that we might need to know?

“With these initial questions it appears that you are eligible for the next step in the study. The next step involves a physical evaluation by a physical therapist and geriatrician here at the Center on Aging. The evaluation will take approximately one hour. We are now scheduling participants for \_\_\_\_\_. Would you be able to come to the Center on Aging to participate during this time?”

If NO: “We will be continuing to test more participants in the coming weeks and months. Can we contact you to schedule a time in future?”

“We like to schedule to start in the morning or after lunch around 1:00.....\*schedule a time with them.

Is participant interested?

a. Visit scheduled \_\_\_\_\_

b. Visit delayed (specify reason)\_\_\_\_\_

c. Subject requests delay and reinquiry at a later date: \_\_\_\_\_

d. Subject and/or family expresses wish for no further contact.

Notes:

*Health Screen For PD Participants*

Phone #:

Address:

Subject Identification Number:

Date of Screen:

Subject name: \_\_\_\_\_  
Last First

“My name is \_\_\_\_\_. I am calling from the Biodynamics Laboratory at the University of Kansas. I was given your name by Dr. Lyons and Dr. Pahwa in the Parkinson’s Disease Center at KUMC as someone who had indicated an interest in participating in a research study. We are now beginning a study looking at how Parkinson’s disease affects the ability of the brain to control our balance and how that might be related to risk of falling. If you think you might be interested in participating, and you have a few minutes, I’d like to describe the study to you.”

Is subject interested? YES NO

Comments: \_\_\_\_\_  
\_\_\_\_\_

If NO: “Thank you for your time. Would you be interested in being contacted for future studies or do you prefer that your name is removed from our list?”

Comments: \_\_\_\_\_  
\_\_\_\_\_

If YES: “Please feel free to ask questions at any time. This study is a one-time evaluation that will look at how Parkinson’s disease affects the ability of the brain to control our balance. We will be looking at those with Parkinson’s compared to healthy adults in the same age range. There are two parts to this study. First, there is a medical screening procedure. The first part is done over the phone and will take approximately 20 minutes. This will include questions about current and previous health conditions. Once that is completed we will schedule you for a visit to the Biodynamics Laboratory at KU in Lawrence where we will do a physical assessment that and then do the balance testing. For the balance testing, we will ask you to do four different tests: one that just involves standing still, one that involves starting to walk from rest, one that involves walking on a treadmill for about 5 minutes, and a balance recovery test. For the balance recovery test, we will pull you backwards from the waist and you will have to regain your balance. During all of the tests, you will be wearing a protective harness to ensure your safety. The whole test will take approximately 3 hours. There is no cost for participating in this study, nor are there any direct benefits to you. We will pay you \$30 for your participation. If you are still interested, I would like to ask you some questions to see if you would be able to participate in this study.”

Notes: \_\_\_\_\_  
\_\_\_\_\_

\*\*If subject is excluded by any questions, stop the interview and explain to the subject the reason for exclusion. Thank them for their time and willingness to participate.

Name: \_\_\_\_\_ Age: \_\_\_\_\_  
Birthdate: \_\_\_\_\_  
Gender:        M        F  
Address: \_\_\_\_\_  
Phone: \_\_\_\_\_  
Schooling/Occupation: \_\_\_\_\_  
Height: \_\_\_\_\_ Weight: \_\_\_\_\_  
Are you currently participating in any other research studies?

This study will be done at the University of Kansas Lawrence Campus. Would you have transportation for this visit?

Are you able to get out of bed and also use the bathroom without assistance from anything or anyone?

Are you able to stand on your own for 10 minutes without assistance?  
(ex. Can you stand at the bathroom sink to do your morning care without having to hold to something?)

#### SUMMARY OF MEDICAL SCREEN:

Pass? If no, why not?

Height: \_\_\_\_\_ Weight: \_\_\_\_\_ Age: \_\_\_\_\_ Gender: \_\_\_\_\_

Comments:

Have you been diagnosed with:	Yes	No	When	Details	Exclude?
Ever had major surgery or amputation?					Yes if affects legs, not recovered completely
Osteoporosis					Yes
Brittle Bones					Yes
Fibromyalgia? Constant aches and fatigue?					Yes if constant
Arthritis					Yes if in legs
Nerve Damage					Yes if in legs
Heart Attack					Yes
Heart Disease or problems (surgeries, valve replacement, angina, pacemaker?)					Yes
Chest Pain from heart disease?					Yes
Polio or Post Polio Syndrome					Yes
Broken Bones? Compression fractures?					Yes if < 2 years ago and in leg or spine
Ever had a hip, knee, or ankle replacement or surgery?					Yes
Ever had a joint fusion?					Yes
Diabetes? Thyroid conditions?					Yes if not controlled or if have neuropathy
High Blood Pressure					Yes if not controlled on meds
Neurological Disease (MS, ALS, Dementia, Seizure disorders)					Yes
Stroke or TIA					Yes
Cancer, Leukemia, Lymphoma?					Yes if currently being treated
Anemia					Yes if has had blood transfusion in last year
Seizure					Yes
Meniere's Disease? Inner Ear Damage? Vertigo? Ear infection right now?					Yes
Acoustic Neuroma? Tinnitus? (ringing, buzzing in ears) Do you feel pressure in ears?					Yes if constant
Do you have any problems with:	Yes	No	How does it affect ADL?		Exclude?
Pain or stiffness in hips? Knee? Ankles? Back? Shoulder?					Yes if affects walking, standing
Hip, Knee, or Ankle injury?					Yes if affects walking, standing
Back Problems? If yes: What motions cause pain (bending, twisting, lifting, quick movements?) How irritable is the pain? How do you treat the pain? Have you seen a doctor?					Yes if brought on by walking, standing, quick movements, if brought on quickly

Muscle Problems in leg? Weakness in legs? Does it limit how far you can walk or how long you can stand?				Yes if affects walking, standing
Poor circulation in legs causing them to become cold, numb, or causes cramping while walking, been diagnosed with PVD? Claudication?				Only if causes problems when walking or standing
Lung disease? Emphhezema? Chronic Bronchitis? SOB? DOE?				Yes if affects walking, standing
Ever had a head or neck injury?				Not necessarily
Gout or Psuedogout?				Not necessarily
Foot problems?				Not necessarily
Hearing Problems? Hearing aid? Last hearing exam?				Not necessarily
Have you been hospitalized in the past year? Major illness in last year?				Not necessarily
Headaches				Not necessarily
Neuropathy				Not necessarily
Vision				Not necessarily
Falls				Not necessarily
Driving				Not necessarily
Night Driving				Not necessarily
Shortness of Breath				Not necessarily
Edema (swelling of legs)				Not necessarily
Fainting or lightheadedness?				Not necessarily
Memory				Not necessarily
Burning pain or weakness anywhere in body?				Not necessarily
Depression				Not necessarily

#### MEDICATIONS:

What medications are you currently taking?

Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_  
Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_  
Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_  
Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_  
Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_  
Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_  
Name: \_\_\_\_\_ Amt \_\_\_\_\_ Time \_\_\_\_\_

\*\*Testing should occur 1-2 hours after last dose of medication.

OTC Medications:

ACTIVITY:

Are you able to leave house / apartment on your own? How often?

When you walk, do you walk with :      Self      walker/cane      person assist      unable

How far do you walk on a daily basis? \_\_\_\_\_

How often do you walk? \_\_\_\_\_

How long do you walk (duration) \_\_\_\_\_

Do you participate in any exercise/Activities?

Type \_\_\_\_\_

Sessions per week \_\_\_\_\_

Minutes / hours per session \_\_\_\_\_

When you transfer from a sitting to standing position, do you do it:

Alone    With assistive device    With person assist      Unable

When you transfer from lying down to sitting, do you do it:

Alone    With assistive device    With person assist      Unable

Hand dominance              L              R

(Right or left-handed?)

Leg dominance L              R

(Which leg would you kick a ball with?)

Recent vision screen? If yes, when?

Is there anything else you can think of about your current or past health state that we might need to know?

When were you first diagnosed with Parkinson's disease?

What was the first symptom you experienced? When did you experience the first symptom?

Are you affected on one or both sides of your body? Which side is more affected?

Do you feel like you have bad balance? Do you have difficulty maintaining your balance while: standing still, walking, changing positions?

Have you fallen in the past year?

Event: \_\_\_\_\_ Date: \_\_\_\_\_ Injury: \_\_\_\_\_

Circumstances: \_\_\_\_\_

Event: \_\_\_\_\_ Date: \_\_\_\_\_ Injury: \_\_\_\_\_

Circumstances: \_\_\_\_\_

Event: \_\_\_\_\_ Date: \_\_\_\_\_ Injury: \_\_\_\_\_

Circumstances: \_\_\_\_\_

How often do you fall?

Do you currently use any devices to assist you (canes, walker, etc?)

“With these initial questions it appears that you are eligible for this study. We are now scheduling participants for \_\_\_\_\_. Would you be able to come to the Center on Aging to participant during this time?”

If NO: “We will be continuing to test more participants in the coming weeks and months. Can we contact you to schedule a time in future?”

“We like to schedule to start in the morning or after lunch around 1:00.....\*schedule a time with them.

Is participant interested?

- a. Visit scheduled \_\_\_\_\_
- b. Visit delayed (specify reason)\_\_\_\_\_
- c. Subject requests delay and reinquiry at a later date: \_\_\_\_\_
- d. Subject and/or family expresses wish for no further contact.

Notes:



*Appointment Letter*



October 13, 2010

Dear,

Thank you for agreeing to participate in our research study! This study looking at how Parkinson's disease affects balance will be conducted in the Biodynamics Lab, which is located on the second floor of Learned Hall on the University of Kansas Lawrence Campus.

Your appointment is scheduled for Wed, Oct. 20<sup>th</sup> at 3pm and will be about 3 hours long. Directions and a campus map are included with this letter. Parking is located on the east side of Eaton Hall (Learned is adjacent to Eaton Hall), and one of four meters will be hooded and marked "Reserved"- this is for you. A research associate will be there to meet you and take you up to the research lab. If you have any problems finding anything please give me a call at the number below.

If you have any questions or need to reschedule your appointment, please contact Molly McVey at 785-218-2714.

Thanks again for participating.

Sincerely,

Molly McVey

Graduate Research Assistant

Biodynamics Laboratory- Mechanical Engineering Department

The University of Kansas

*Physical Examination Data*

Height		Weight				
Sitting BP-P						
Supine BP-P		Standing BP-P				
Strength	<i>Left</i>	<i>Right</i>		<i>Left</i>	<i>Right</i>	
Shld Abd			Hip Ext			
Biceps			Hip Abd			
Triceps			Hip Add			
Wst Flex			Knee Ext			
Wst Ext			Knee Flex			
Grip			Ankle Df			
Hip Flex			Ankle Pf			
Reflexes			Patellar			
Biceps			Achilles			
Triceps			Babinski			
Sensory	Position		Vibration		Pin Prick	
	<i>Left</i>	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>	<i>Right</i>
Upp Ext						
Low Ext						
Cerebellar	<i>Left</i>	<i>Right</i>				
Fing-Nose						
Heel-Shin						
Other/comments						

Examiner Name: \_\_\_\_\_

## MMSE Questionnaire

# Mini-Mental State Examination (MMSE)<sup>1,2\*</sup>

Make the patient comfortable and establish rapport. Ask questions in the order listed. *Total possible score is 30.*

Maximum  
Score    Score

### ORIENTATION

- 5    (   )    1. "What is the (year) (season) (date) (day) (month)?"
- 5    (   )    2. "Where are we?" (state) (county) (town or city) (hospital) (floor).

### REGISTRATION

- 3    (   )    Ask the patient if you may test his/her memory. Then say the names of 3 unrelated objects, clearly and slowly, about one second for each (eg, "apple," "table," "penny"). After you have said all 3, ask him/her to repeat them. This first repetition determines the score (0-3), but keep saying them until he/she can repeat all 3, up to 6 trials.

### ATTENTION AND CALCULATION

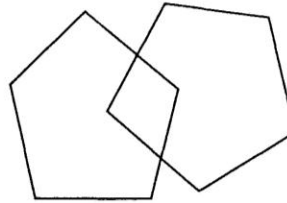
- 5    (   )    Ask the patient to begin with 100 and count backwards by 7. Stop after 5 subtractions (93, 86, 79, 72, 65). Score the total number of correct answers. If the patient cannot or will not perform the serial 7s task, ask him/her to spell the word "WORLD" backwards. The score is the number of letters in the correct order (eg, DLROW = 5; DLRW = 4; DLORW, DLW = 3; OW = 2; DRLWO = 1).

### RECALL

- 3    (   )    Ask the patient to recall the 3 items repeated above (eg, "apple," "table," "penny").

### LANGUAGE

- 2    (   )    **Naming:** Show the patient a wristwatch and ask him/her what it is. Repeat for pencil.
- 1    (   )    **Repetition:** Ask the patient to repeat the phrase "No ifs, ands, or buts" after you.
- 3    (   )    **3-Stage Command:** Give the patient a piece of blank paper and ask him/her to "take a piece of paper in your right hand, fold it in half, put it on the floor." Score 1 point for each part correctly executed.
- 1    (   )    **Reading:** On a blank piece of paper, print the sentence "CLOSE YOUR EYES" in letters large enough for the patient to see clearly. Ask him/her to read it and do what it says. Score 1 point only if he/she actually closes his/her eyes.
- 1    (   )    **Writing:** Give the patient a blank piece of paper and ask him/her to write a sentence. Do not dictate a sentence; it is to be written spontaneously. It must contain a subject and verb and be sensible. Correct grammar and punctuation are not necessary.
- 1    (   )    **Copying:** Ask the patient to copy the figure of intersecting pentagons exactly as it is. All 10 angles must be present and 2 must intersect to form a 4-sided figure to score 1 point. Tremor and rotation are ignored.



<b>Maximum</b>	<b>Total</b>	<i>Suggested guideline for determining the severity of cognitive impairment:</i>
<b>Total Score</b>	<b>Score</b>	
30	(      )	
		Mild: MMSE ≥21
		Moderate: MMSE 10-20
		Severe: MMSE ≤9
<i>Expected decline in MMSE scores in untreated mild to moderate Alzheimer's patient is 2 to 4 points per year.<sup>3,4</sup></i>		

\* Adapted from Folstein et al<sup>1</sup> and Cockrell and Folstein.<sup>2</sup> © 1975, 1998 Mini Mental LLC. Used with permission.

**References:** 1. Folstein MF, Folstein SE, McHugh PR. "Mini-Mental State": a practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res.* 1975;12:189-198. 2. Cockrell JR, Folstein MF. Mini-Mental State Examination (MMSE). *Psychopharm Bull.* 1988;24:689-692. 3. Becker JT, Huff FJ, Nebes RD, Holland A, Boller F. Neuropsychological function in Alzheimer's disease: pattern of impairment and rates of progression. *Arch Neurol.* 1988;45:263-268. 4. Mortimer JA, Ebbitt B, Jun S-P, Finch MD. Predictors of cognitive and functional progression in patients with probable Alzheimer's disease. *Neurology.* 1992;42:1689-1696.

Beck Depression Index

# **BDI**

Name: \_\_\_\_\_ Date \_\_\_\_\_

This questionnaire consists of 21 groups of statements. After reading each group of statements carefully, circle the number (0, 1, 2, or 3) next to the one statement in each group which best describes the way you have been feeling the past week, including today. If several statements within a group seem to apply equally well, circle each one. Be sure to read all the statements in each group before making your choice.

- |   |   |
|---|---|
| <p><b>1</b> 0 I do not feel sad.<br/>1 I feel sad.<br/>2 I am sad all the time and I can't snap out of it.<br/>3 I am so sad or unhappy that I can't stand it.</p> <p><b>2</b> 0 I am not particularly discouraged about the future.<br/>1 I feel discouraged about the future.<br/>2 I feel I have nothing to look forward to.<br/>3 I feel that the future is hopeless and that things cannot improve.</p> <p><b>3</b> 0 I do not feel like a failure.<br/>1 I feel I have failed more than the average person.<br/>2 As I look back on my life, all I can see is a lot of failures.<br/>3 I feel I am a complete failure as a person.</p> <p><b>4</b> 0 I get as much satisfaction out of things as I used to.<br/>1 I don't enjoy things the way I used to.<br/>2 I don't get real satisfaction out of anything anymore.<br/>3 I am dissatisfied or bored with everything.</p> <p><b>5</b> 0 I don't feel particularly guilty.<br/>1 I feel guilty a good part of the time.<br/>2 I feel quite guilty most of the time.<br/>3 I feel guilty all of the time.</p> <p><b>6</b> 0 I don't feel I am being punished.<br/>1 I feel I may be punished.<br/>2 I expect to be punished.<br/>3 I feel I am being punished.</p> | <p><b>7</b> 0 I don't feel disappointed in myself.<br/>1 I am disappointed in myself.<br/>2 I am disgusted with myself.<br/>3 I hate myself.</p> <p><b>8</b> 0 I don't feel I am any worse than anybody else.<br/>1 I am critical of myself for my weaknesses or mistakes.<br/>2 I blame myself all of the time for my faults.<br/>3 I blame myself for everything bad that happens.</p> <p><b>9</b> 0 I don't have any thoughts of killing myself.<br/>1 I have thoughts of killing myself, but I would not carry them out.<br/>2 I would like to kill myself.<br/>3 I would kill myself if I had the chance.</p> <p><b>10</b> 0 I don't cry more than usual.<br/>1 I cry more now than I used to.<br/>2 I cry all the time now.<br/>3 I used to be able to cry, but now I can't cry even though I want to.</p> <p><b>11</b> 0 I am no more irritated now than I ever am.<br/>1 I get annoyed or irritated more easily than I used to.<br/>2 I feel irritated all the time now.<br/>3 I don't get irritated at all by the things that used to irritate me.</p> |
|---|---|

- 12 0 I have not lost interest in other people.  
1 I am less interested in other people than I used to be.  
2 I have lost most of my interest in other people.  
3 I have lost all of my interest in other people.

- 13 0 I make decisions about as well as I ever could.  
1 I put off making decisions more than I used to.  
2 I have greater difficulty in making decisions than before.  
3 I can't make decisions at all anymore.

- 14 0 I don't feel I look any worse than I used to.  
1 I am worried that I am looking old or unattractive.  
2 I feel that there are permanent changes in my appearance that make me look unattractive.  
3 I believe that I look ugly.

- 15 0 I can work about as well as before.  
1 It takes an extra effort to get started at doing something.  
2 I have to push myself very hard to do anything.  
3 I can't do any work at all.

- 16 0 I can sleep as well as usual.  
1 I don't sleep as well as I used to.  
2 I wake up 1-2 hours earlier than usual and find it hard to get back to sleep.  
3 I wake up several hours earlier than I used to and cannot get back to sleep.

- 17 0 I don't get more tired than usual.  
1 I get tired more easily than I used to.  
2 I get tired from doing almost anything.  
3 I am too tired to do anything.

- 18 0 My appetite is no worse than usual.  
1 My appetite is not as good as it used to be.  
2 My appetite is much worse now.  
3 I have no appetite at all anymore.

- 19 0 I haven't lost much weight, if any, lately.  
1 I have lost more than 5 pounds.  
2 I have lost more than 10 pounds.  
3 I have lost more than 15 pounds.

I am purposely trying to lose weight by eating less. Yes \_\_\_\_\_ No \_\_\_\_\_

- 20 0 I am no more worried about my health than usual.  
1 I am worried about physical problems such as aches and pains; or upset stomach; or constipation.  
2 I am very worried about physical problems and it's hard to think of much else.  
3 I am so worried about my physical problems that I cannot think about anything else.

- 21 0 I have not noticed any recent change in my interest in sex.  
1 I am less interested in sex than I used to be.  
2 I am much less interested in sex now.  
3 I have lost interest in sex completely.

*Barthel Index*

INSTRUCTIONS: The Barthel Index is a record of what a patient does **not** a record of what a patient could do. Full credit is not given for an activity if the patient needs even minimal help/supervision. A score of (0) is given when a patient cannot meet the criteria as defined. Circle the appropriate answer to each question.

1. Today, are you able to feed yourself?  
10: Independent; feeds self from tray or table; can put on assistive device if needed; accomplishes feeding in reasonable time.  
5: Assistance necessary with cutting food, etc.  
0: Cannot meet criteria  
88: Contraindicated due to \_\_\_\_\_
2. Today, are you able to get out of bed or into a chair?  
15: Independent in all phases of this activity  
10: Minimal help needed or patient needs to be reminded or supervised for safety of one or more parts of this activity.  
5: Patient can come to sitting position without help of second person, but needs to be lifted out of bed and assisted with transfers  
0: Cannot meet criteria  
88: Contraindicated due to \_\_\_\_\_
3. Today, are you able to wash your face, brush your teeth, brush your hair, etc.?  
5: Can wash hands, face; combs hair, cleans teeth. Can shave (males) or apply makeup (females) without assistance; females need not braid or style hair.  
0: Cannot meet criteria  
88: Contraindicated due to \_\_\_\_\_
4. Today are you able to get on and off the toilet?  
10: Able to get on and off the toilet, fastens/unfastens clothes; can use toilet paper without assistance. May use wall bar or other support if needed; if bedpan is necessary, patient can place it on chair, empty, and clean it.  
5: Needs help because of imbalance or other problems with clothes or toilet paper  
0: Cannot meet criteria  
88: Contraindicated due to \_\_\_\_\_
5. Today, are you able to bathe yourself?  
5: May use tub, shower, or sponge bath. Patient must be able to perform all functions without another person being present.  
0: Cannot meet criteria  
88: Contraindicated due to \_\_\_\_\_
6. Today, are you able to walk without help?  
15: Patient can walk at least 50 yards without assistance or supervision; may use braces, prostheses, crutches, canes, or walker, but not a rolling walker. Must be able to lock/unlock braces, assume standing or seated position, get mechanical aids into position for use and dispose of the mechanical aids when seated (putting on and off braces should be scored under dressing).  
10: Assistance needed to perform above activities, but can walk 50 yards with little help.  
0: Cannot meet criteria  
88: Contraindicated due to \_\_\_\_\_

7. Today, are you able to use a wheelchair? (Do not score if patient competes score for walking-item #6).
- 5: Patient cannot ambulate, but can propel wheelchair independently; can go around corners, turn around and maneuver chair to table, bed, toilet, etc; must be able to push chair 50 yards.
- 0: Cannot meet criteria
- 88: Contraindicated due to \_\_\_\_\_
8. Today, are you able to walk up and down stairs?
- 10: Able to go up and down flights of stairs safely without supervision; using canes, handrails, or crutches when needed and can carry these items as ascending/descending.
- 5: Needs help or supervision of any of the above items.
- 0: Cannot meet criteria
- 88: Contraindicated due to \_\_\_\_\_
9. Today, are you able to dress and undress yourself?
- 10: Able to put on, fasten, and remove all clothing; ties shoelaces unless necessary adaptations used. Activity includes fastening braces and corsets when prescribed; suspenders, loafer shoes, and dresses opening in the front may be used when necessary.
- 5: Needs help putting on, fastening, or removing clothing; must accomplish at least half of task alone within reasonable time; women need not be scored on use of brassiere or girdle unless prescribed.
- 0: Cannot meet criteria
- 88: Contraindicated due to \_\_\_\_\_
10. Today, are you able to control your bowels?
- 10: Able to control bowels and have no accidents. Can use a suppository or take an enema when necessary (as for spinal cord injury patients who have had bowel training).
- 5: Needs help in using a suppository or taking an enema or has occasional accidents.
- 0: Cannot meet criteria
- 88: Contraindicated due to \_\_\_\_\_
11. Today, are you able to control your bladder?
- 10: Able to control bladder day and night. Spinal injury patients must be able to put on external devices and leg bags independently, clean and empty bag, and must stay dry day and night.
- 5: Occasional accidents occur, cannot wait for bedpan, does not get to toilet in time or needs help with external device.
- 0: Cannot meet criteria
- 88: Contraindicated due to \_\_\_\_\_
12. Information for today's Barthel data gathered from:
- 01: Patient
- 02: Proxy- Caregiver
- 03: Proxy- Other
- 04: Chart
- 05: Both patient and proxy

*Environmental Assessment*

1. Do you live in a home, apartment, or assisted living facility?

2. Do you have stairs in your home? How often do you use them?

Staircase #1: \_\_\_\_\_ Frequency: \_\_\_\_\_

Staircase #2: \_\_\_\_\_ Frequency: \_\_\_\_\_

Staircase #3: \_\_\_\_\_ Frequency: \_\_\_\_\_

Staircase #4: \_\_\_\_\_ Frequency: \_\_\_\_\_

3. Do you live alone? With a spouse or partner? Do you have a caretaker (live-in or otherwise)?

4. Do you use any type of assistive devices at any time during a normal day? (Walkers, canes, etc?)

5. Do you ever use assistance from someone else during a normal day? (Taking a hand to go down steps, get out of a car, etc.)?

6. Have you ever modified anything in your home to reduce the risk of falling? When?

Modification: \_\_\_\_\_ Date: \_\_\_\_\_

Modification: \_\_\_\_\_ Date: \_\_\_\_\_

Modification: \_\_\_\_\_ Date: \_\_\_\_\_

Modification: \_\_\_\_\_ Date: \_\_\_\_\_

Modification: \_\_\_\_\_ Date: \_\_\_\_\_



## UPDRS Assessment

BINDING LINE	
<div style="border-bottom: 1px solid black; margin-bottom: 5px;">University of Kansas Medical Center 3901 Rainbow Boulevard Kansas City, KS 66160 Department of Neurology</div> <div style="border-bottom: 1px solid black; margin-bottom: 5px;">Patient Name _____</div> <div style="border-bottom: 1px solid black;">Med. Rec. No. _____</div>	<div style="display: flex; justify-content: space-around; margin-top: 20px;"><span><input type="checkbox"/> Meds Off</span><span><input type="checkbox"/> Meds On</span></div>

**I. MENTATION, BEHAVIOR AND MOOD**

**1. Intellectual Impairment**.....  
0 = None  
1 = Mild. Consistent forgetfulness with partial recollection of events and no other difficulties  
2 = Moderate memory loss, with disorientation and moderate difficulty handling complex problems. Mild but definite impairment of function at home with need of occasional prompting.  
3 = Severe memory loss with disorientation for time and often to place. Severe impairment in handling problems.  
4 = Severe memory loss with orientation preserved to person only. Unable to make judgements or solve problems. Requires much help with personal care. Cannot be left alone at all.  
9 = Information Missing

**2. Thought Disorder**.....  
0 = None  
1 = Vivid dreaming.  
2 = "Benign" hallucinations with insight retained.  
3 = Occasional to frequent hallucinations or delusions; without insight; could interfere with daily activities.  
4 = Persistent hallucinations, delusions, or florid psychosis. Not able to care for self.  
9 = Information Missing

**3. Depression**.....  
0 = Not present  
1 = Periods of sadness or guilt greater than normal, never sustained for days or weeks.  
2 = Sustained depression (1 week or more).  
3 = Sustained depression with vegetative symptoms (insomnia, anorexia, weight loss, loss of interest).  
4 = Sustained depression with vegetative symptoms and suicidal thoughts or intent.  
9 = Information Missing

**4. Motivation / Initiative**.....  
0 = Normal  
1 = Less assertive than usual; more passive.  
2 = Loss of initiative or disinterest in elective (non-routine) activities.  
3 = Loss of initiative or disinterest in day-to-day (routine) activities.  
4 = Withdrawn, complete loss of motivation.  
9 = Information Missing

**5. Total Mentation Score**.....

**II. ACTIVITIES OF DAILY LIVING**

**6. Speech**.....  
0 = Normal  
1 = Mildly affected. No difficulty being understood.  
2 = Moderately affected. Sometimes asked to repeat statements.  
3 = Severely affected. Frequently asked to repeat statements.  
4 = Unintelligible most of the time.  
9 = Information Missing

Date \_\_\_\_\_

**UPDRS**

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7. Salivation .....  
0 = Normal  
1 = Slight but definite excess of saliva in mouth; may have nighttime drooling.  
2 = Moderately excessive saliva; may have minimal drooling.  
3 = Marked excess of saliva with some drooling.  
4 = Marked drooling, requires constant tissue or handkerchief.  
9 = Information Missing
8. Swallowing .....  
0 = Normal  
1 = Rare choking.  
2 = Occasional choking.  
3 = Requires soft food.  
4 = Requires NG tube or gastrostomy feeding.  
9 = Information Missing
9. Handwriting.....  
0 = Normal  
1 = Slightly slow or small.  
2 = Moderately slow or small; all words are legible.  
3 = Severely affected; not all words are legible.  
4 = The majority of words are not legible.  
9 = Information Missing
10. Cutting food and handling utensils.....  
0 = Normal  
1 = Somewhat slow and clumsy, but no help needed.  
2 = Can cut most foods, although clumsy and slow; some help needed.  
3 = Food must be cut by someone, but can still feed slowly.  
4 = Needs to be fed.  
9 = Information Missing
11. Dressing.....  
0 = Normal  
1 = Somewhat slow, but no help needed.  
2 = Occasional assistance with buttoning, getting arms in sleeves.  
3 = Considerable help required, but can do some things alone.  
4 = Helpless.  
9 = Information Missing
12. Hygiene .....  
0 = Normal  
1 = Somewhat slow, but no help needed.  
2 = Needs help to shower or bathe; or very slow in hygienic care.  
3 = Requires assistance for washing, brushing teeth, combing hair, going to bathroom.  
4 = Foley catheter or other mechanical aids.  
9 = Information Missing
13. Turning in bed and adjusting bed clothes.....  
0 = Normal  
1 = Somewhat slow and clumsy, but no help needed.  
2 = Can turn alone or adjust sheets, but with great difficulty.  
3 = Can initiate, but not turn or adjust sheets alone.  
4 = Helpless.  
9 = Information Missing

Date \_\_\_\_\_

UPDRS

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BINDING LINE

University of Kansas Medical Center  
3901 Rainbow Boulevard Kansas City, KS 66160  
Department of Neurology

☐ Meds Off

☐ Meds On

Patient Name \_\_\_\_\_

Med. Rec. No. \_\_\_\_\_

14. Falling (unrelated to freezing).....

- 0 = None
- 1 = Rare falling.
- 2 = Occasionally falls, less than once per day.
- 3 = Falls an average of once daily.
- 4 = Falls more than once daily.
- 9 = Information Missing

15. Freezing when walking .....

- 0 = None
- 1 = Rare freezing when walking; may have start-hesitation.
- 2 = Occasional freezing when walking.
- 3 = Frequent freezing. Occasionally falls from freezing.
- 4 = Frequent falls from freezing.
- 9 = Information Missing

16. Walking.....

- 0 = Normal
- 1 = Mild difficulty. May not swing arms or may tend to drag leg.
- 2 = Moderate difficulty, but requires little or no assistance.
- 3 = Severe disturbance of walking, requiring assistance.
- 4 = Cannot walk at all, even with assistance.
- 9 = Information Missing

17. Tremor ..... R \_\_\_\_\_

- 0 = Absent
- 1 = Slight and infrequently present.
- 2 = Moderate; bothersome to patient.
- 3 = Severe; interferes with many activities.
- 4 = Marked, interferes with most activities.
- 9 = Information Missing

L \_\_\_\_\_

18. Sensory complaints related to Parkinsonism .....

- 0 = None
- 1 = Occasionally has numbness, tingling, or mild aching.
- 2 = Frequently has numbness, tingling, or aching; not distressing.
- 3 = Frequent painful sensations.
- 4 = Excruciating pain.
- 9 = Information Missing

19. Total Activities of Daily Living Score.....

Date \_\_\_\_\_

UPDRS

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### III. MOTOR EXAMINATION

#### 20. Speech.....

- 0 = Normal
- 1 = Slight loss of expression, diction and/or volume.
- 2 = Monotone, slurred but understandable; moderately impaired.
- 3 = Marked impairment, difficult to understand.
- 4 = Unintelligible.
- 9 = Information Missing

#### 21. Facial expression .....

- 0 = Normal
- 1 = Minimal hypomimia, could be normal "poker face".
- 2 = Slight but definitely abnormal diminution of facial expression.
- 3 = Moderate hypomimia; lips parted some of the time.
- 4 = Marked of fixed facies with severe or complete loss of facial expression; lips parted ¼ inch or more.
- 9 = Information Missing

#### 22. Tremor at rest ..... JAW \_\_\_\_\_

- 0 = Absent
- 1 = Slight and infrequently present.
- 2 = Moderate in amplitude, but only intermittently present.
- 3 = Moderate in amplitude and present most of the time.
- 4 = Marked in amplitude and present most of the time.
- 9 = Information Missing

RU \_\_\_\_\_  
LU \_\_\_\_\_  
RL \_\_\_\_\_  
LL \_\_\_\_\_

#### 23. Action of postural tremor of hands ..... R \_\_\_\_\_

- 0 = Absent
- 1 = Slight and infrequent
- 2 = Moderate in amplitude, present with action.
- 3 = Moderate in amplitude with posture holding as well as action.
- 4 = Marked in amplitude; interferes with feeding.
- 9 = Information Missing

L \_\_\_\_\_

#### 24. Rigidity..... NECK \_\_\_\_\_

Judged on passive movement of major joints with patient relaxed in sitting position. Cogwheeling to be ignored.

- 0 = Absent
- 1 = Slight or detectable only when activated by mirror or other movements.
- 2 = Mild to moderate.
- 3 = Marked, but full range of motion easily achieved.
- 4 = Severe, range of motion achieved with difficulty.
- 9 = Information Missing

RU \_\_\_\_\_  
LU \_\_\_\_\_  
RL \_\_\_\_\_  
LL \_\_\_\_\_

#### 25. Finger taps ..... R \_\_\_\_\_

- 0 = Normal (>= 15/5 sec)
- 1 = Mild slowing and/or reduction in amplitude (11-14/5 sec)
- 2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement. (7-10/5 sec)
- 3 = Severely impaired. Frequent hesitation in initiating movement or arrests in ongoing movement. (3-6/5 sec)
- 4 = Can barely raise index finger. (0-2/5 sec)
- 9 = Information missing

L \_\_\_\_\_

#### 26. Hand movements..... R \_\_\_\_\_

Patient opens and closes hands in rapid succession with widest amplitude possible, each hand separately.

- 0 = Normal
- 1 = Mild slowing and/or reduction in amplitude.
- 2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
- 3 = Severely impaired. Frequent hesitation in initiating movement or arrests in ongoing movement.
- 4 = Can barely perform the task.
- 9 = Information missing

L \_\_\_\_\_

Date \_\_\_\_\_

UPDRS

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34. Body bradykinesia and hypokinesia .....  
*Combining slowness, hesitancy, decreased arm swing, small amplitude, and poverty of movement in general.*  
0 = None  
1 = Minimal slowness, giving movement a deliberate character; could be normal for some persons.  
2 = Mild degree of slowness and poverty of movement which is definitely abnormal. Alternatively, some reduced amplitude.  
3 = Moderate slowness, poverty or small amplitude of movement.  
4 = Marked slowness, poverty or small amplitude of movement.  
9 = Information Missing

35. Total Motor Exam Score .....

TOTAL Unified Parkinson's Disease Rating Scale (UPDRS) Score .....

#### IV. COMPLICATIONS OF THERAPY

##### A. Dyskinesias

36. Duration .....  
*What proportion of the waking day are dyskinesias present?*  
0 = None  
1 = 1% - 25% of day.  
2 = 26% - 50% of day.  
3 = 51% - 75% of day.  
4 = 76% - 100% of day.  
9 = Information Missing

37. Disability .....  
*How disabling are the dyskinesias?*  
0 = Not disabling.  
1 = Mildly disabling.  
2 = Moderately disabling.  
3 = Severely disabling.  
4 = Completely disabling.  
9 = Information Missing

38. Painful dyskinesias .....  
*How painful are the dyskinesias?*  
0 = No painful dyskinesias  
1 = Slight  
2 = Moderate  
3 = Severe  
4 = Marked  
9 = Information Missing

39. Presence of early morning dystonia .....  
0 = No  
1 = Yes  
9 = Information Missing

##### B. Clinical fluctuations

40. Are any "off" periods predictable as to timing after a dose of medications? .....  
0 = No  
1 = Yes  
9 = Information Missing

41. Are any "off" periods unpredictable as to timing after a dose of medication? .....  
0 = No  
1 = Yes  
9 = Information Missing

Date .....

UPDRS

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Impressions

Plan

Return to clinic

Signature

Date

UPDRS

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## APPENDIX D: EXPERIMENTAL PROTOCOL DOCUMENTATION

## *Technical Setup and Data Acquisition Protocol*

### *Data Acquisition Setup*

Setup data files on both the labview and optotrak computers. For the labview computer, setup a folder for each subject in each task folder. My documents→Research→Molly→PD Project 2010→Data→BR, GI, Sway, Gait, etc. For the optotrak computer, just setup a subject folder in the PD Project→Data folder. It is imperative to keep track of which optotrak file goes with which data file from the other computer. I usually do this on the data collection sheet.

Decide the order of tasks for the experiment and order of EO/EC trials for sway. Balance Recovery will always go first. Use “randperm(3)” to determine the order of the other tasks. 1= gait initiation, 2= sway, 3= gait. For sway, use “randperm(6)” and each even number it gives= eyes open trial, and each odd number= eyes closed trial. Write the orders on the data collection sheet and on the the whiteboard.

### *Loading the Pull Device*

Take the subject's weight on the force plate. Add 10 lbs to account for the weight of all of the sensors and rigid harness.

Go to the “Pull Weight Combinations” sheet and look up the weight to add amount. Remember that the actual amount of weight you will add is 7 lbs less than what it says in the “weight to add” column. If you add the weight together from the weight combinations that it gives, that is the right amount to add. Or, you can just subtract 7 lbs from the amount it tells you to add.

To determine the drop distance, measure the distance from the middle of the waist harness loop that the rope connects in to the floor. Take 8.7% of this number and then add 0.5cm. So the calculation is waist height\*.087 + 0.5 cm.

To set the drop distance, note that a “zero” distance is 11cm on the meter stick that is in the device. So you will want to move the brushes to whatever drop distance you calculated + 11cm.

### *Optotrak Setup*

Place Optotrak sensors in location- 12 feet from midline of force plates on East and West sides

Connect 3020 and Certus sensors to the SCU using the correct cables (they are labeled). Ensure that the cable from the SCU to the computer is connected, and that the power is connected.

Turn on both sensors and the SCU unit.

Start up the optotrak computer, logon, and open First Principles

Choose File→New Experiment

Perform a new registration and alignment with coordinate system origin at the SE corner of force plate #3.

\*Note- if the software does not detect both sensors it will not ask you to perform a registration- make sure that it finds both sensors. If it doesn't, try “Query System,” and then start the setup over again.

Note that sensor 3-03-63 is the 3020 system.

Connect all markers and strobers and make sure the software recognizes the correct number of markers.

You can go through and name them here as well if you want to.

Choose to enable the trigger

Setup your data collection parameters

Make sure that all markers are visible.

### *Force Plate Setup*

Turn on and leave alone for 10-15 minutes

Balance amplifiers

Take zero trial prior to data collection

### *EMG Setup*

Scrub area with pumice stone and rub with alcohol wipe



Place sensors and arrange wires  
Connect output cables  
Ensure that the gain is turned to 1k on all 8 channels  
Check signal using labview

#### *Labview Startup*

Open My Documents→Research→Molly→PD Project 2010→Labview Vis and open the “PD\_data\_collection\_allinone.”

After balancing force plates, take a force plate zero trial.

-Set collection time to 1 sec

-Select “no” for “Use Trigger?”

-Select “no” for “Do you want to track the COP before data collection?”

-Save the zero trial as My Documents→Research→Molly→PD Project 2010→Data→

Then choose the appropriate experiment folder and label file as “fp\_zero”

#### *For the balance recovery experiment,*

Have the subject stand on force plates one and two in the same position as they will stand for the balance recovery task. Mark the feet with tape. Take a trial and label it “still” This will serve as the static trial, too- so make sure that all markers are visible and use the trigger to collect optotrak data.

Run “zero trial calculation simplify” VI to calculate the still position COP. Save the file as “still\_cop.”

Now open PD\_data\_collection\_allinone and select “yes” to monitor the COP and “yes” to use the trigger. Set the collection time to 5 seconds.

Make sure that the drop mechanism is ready to go (hit “open cleats” and front “drop” and front “cleat” to arm it.

Begin the VI by pushing the start arrow on the upper left hand side of the window.

When the green light comes on (indicating they have met the COP requirements), click on the “GO” button. Now the program is waiting for your trigger.

Press the red trigger button to trigger optotrak, labview, and to drop the weights. Weights are dropped 500ms after data collection begins.

Save the trial as br1. Note on the data collection sheet which optotrak file goes with which data file.

Check that all of the data looks good

#### *For all other tasks,*

-Select “no” for “Do you want to track the COP before data collection?”

Take another fp\_zero trial (1 sec), and save it in the correct task folder.

Gait Initiation trials are 5 seconds (unless they need to be adjusted for a very slow subject), Sway trials are 30 seconds, and we don’t need to collect data through labview for gait trials.

Gait initiation also needs a static trial- only marker data is needed, but all markers must be in view. Static trials are 5 seconds long.

### **Post Data Collection Tasks**

#### *File Backup:*

Take “PD Project Data Transfer” external hard drive from out of Molly’s desk and transfer the optotrak files to the hard drive.

Connect the video camera to the Labview computer and turn it on.

Connect the external hard drive to the Labview computer.

Copy the video and optotrak data to the appropriate folder in the Labview computer.

Copy all files from the labview computer folder to the “Master Backup Hard Drive” (the 1 TB one that sits on the desk by the labview computer) and also to the transfer hard drive.

Double check that you have complete sets of data on both the labview computer, the transfer hard drive, and the master backup hard drive.

Someone should take the transfer hard drive home with them each night.

*DT Timesheet*

Update the spreadsheet “DT Timesheet” with the date and hours that he worked.

*Payment and Thank You’s:*

At the end of a testing week, collect all of the payment forms out of the folders of each participant.

Complete the back side of the forms, and take to Carl to sign.

Make copies of the signed forms for our records and turn in the originals to Leslie in the ME office.

Write and send a thank-you card from our lab to the participant.

*PD Patient Appt. with Dr. Lyons Record*

Dr. Lyons needs to know about each patient that we test and when we test them. Update the spreadsheet called “Testing Dates” to include each PD participant. Really this should be updated as soon as the patient is scheduled in case they go in to see Dr. Pahwa between scheduling and testing.

## Experimental Protocol

**0-45 minutes:** Subject Paperwork, Health Assessments, Measurements

Location: subject setup area

- Consent Form
- Take weight on force plates
- Questionnaires
- Offer a bathroom break!
- Change into shorts, socks, shoes, T-shirt
- Health Assessment, take weight and height
- Measurements

Laying down: Leg Length, ASIS distance, ankle width

Sitting up: calf circumference

Standing: knee width, ankle height, foot width, foot length, thigh circumference

\*While taking measurements, mark placement for Knee Marker, ASIS, great troch, and hamstring EMG.

### Measurement Descriptions:

*Weight:* When the subject first arrives, weigh with shoes and clothes on on force plates. Then, after the subject has changed into testing clothing, weight without shoes on on force plates again.

*ASIS Breadth:* Measure the horizontal distance between the two ASIS

*Thigh length:* Measure the vertical distance between the top of the great troch and the top of the lateral tibia (can use tibial plateau).

*Thigh Circumference:* Measure mid-thigh

*Calf Length:* Measure the vertical distance between the top of the lateral tibia and the lateral malleolus (ankle).

*Calf Circumference:* Measure the circumference of the calf at the largest spot.

*Knee Diameter:* Measure the maximum breadth of the knee across the femoral epicondyles.

*Foot Length:* Measure the distance from the back of the heel to the tip of the longest toe.

*Ankle height:* Measure the vertical distance from the floor to the lateral malleolus.

*Ankle width:* Measure the maximum distance between the medial and lateral malleoli.

*Foot width:* Measure the width across the distal ends of metatarsals 1 and 5.

**45-90 minutes:** Sensor placement and Equipment Setup

Location: Platform Area

Put safety harness on.

*Place EMGs:* bilateral TA, gastroc, hamstring, quad

Connect EMG as follows:

EMG lead	Muscle	EMG out-> DAQ Board Channel in
#1	R TA	1 – 22
#2	R gastroc	2 – 23
#3	R solius/ham	3 – 24
#4	R quad	4 – 25
#5	L TA	5 – 26
#6	L gastroc	6 – 27
#7	L solius/ham	7 – 28
#8	L quad	8 – 29

Test EMGs, take sitting break

#### *Optotrak Markers*

15 markers will be placed on the lower body as follows (see Vaughan's Gait Model and Helen Hayes Marker Set for more information about specific placement methods):

*Complete Setup:* Bilateral – ASIS, sacrum, thigh, knee, shin wand, ankle, heel, toe

*Modified Setup(for balance recovery only):* Bilateral- greater trochanter, thigh, knee, shin wand, ankle, heel, toe

#### Marker Placement Tips:

*ASIS/Sacrum:* tape around the waist, and then attach markers to the tape. Use a foam piece to orient the sacrum towards one of the cameras.

*Thigh:* Find greater trochanter, have subject rotate their foot to make sure you have it, then place marker on the line between the greater troch and knee (along the long axis of the thigh). Marker should be on lower thigh and in line with the flexion/extension axis of the knee.

*Knee:* Identify tibial plateau, then move back and up to find the femoral epicondyle- along the flexion/extension axis of the knee.

*Shin Wand :* Place on lower shank, on long axis, and in line with flexion/extension axis of the ankle.

*Heel:* Place on shoe, at same height of toe marker, use a foam piece to orient the marker towards the cameras.

*Ankle:* Place marker in line of flexion/extension axis of ankle.

*Toe:* 2<sup>nd</sup> metatarsal head on joint closest to body (2<sup>nd</sup> biggest) Use a foam piece to orient the marker towards the cameras.

Walk subject into data collection area and test to make sure all markers are visible.

Subject calibration trial (stand still)

Take a sitting break

#### **90-180 minutes:** Experimental Testing/Data Collection

Location: Platform Area

*Balance Recovery (trial type: general w/analog/ trial name: pull1)*

The balance recovery testing consists of 3 backwards pull trials. Force plate, EMG, and motion data will be collected during all trials. The weight-drop device will be used to pull the participant.

*Should have modified marker setup (no sacrum or ASIS, but including great troch markers)*

Attach safety harness

TAKE STATIC TRIAL IN MODIFIED MARKER SETUP

Mark foot position with tape

Put on the rigid harness

Measure waist height, adjust pull device to 8.7% of waist height

Take a still trial

Mark the feet so they stay in the same position as for the “still trial.”

Attach pull device cable

Read script, explaining task (no practice trials)

Start the video camera

Research assistant should spot the participant throughout all trials

Once subject is ready, release the weight-dropping mechanism

Replace weights and tell the subject to relax after they have regained their balance for three seconds

Check trial for marker visibility

Perform a total of 3 trials with 30 seconds rest in between trials  
Disconnect safety harness, cable to pull device, and remove rigid harness  
Take a sitting break

*Sway (trial type: PD\_sway/ trial name: sway1)*

Sway testing consists of three trials in each of two different conditions, eyes open (EO) and eyes closed (EC). Force plate, EMG, and motion data will be collected. Each test will last 30 seconds with 30 seconds of rest in between trials.

*Should have complete marker setup*

Have participant stand comfortably with one foot on each force plate. Feet should be shoulder wide and at a self-selected angle. Arms rest to the side and the subject is looking at a marker placed 5 feet in front of the at approximately eye height.

Attach safety harness

Check EMG and visibility of markers

Read script to the participant

Before each test, remind the participant of the condition being tested (EO or EC).

Take a sitting break

*Gait Initiation (trial type: general w/analog/ trial name: gait\_ini1)*

Participants will perform 5 gait initiation trials, all starting from standing on a forceplate. EMG, force and movement data will be collected.

*Should have complete marker setup*

Have participant stand in collection area with one foot on each force plate. They will be oriented so that they are looking at the South wall.

Take a static trial

Mark foot position

Attach safety harness

Read the script to the participant.

Subject will start with one foot on each force plate, then step forward when the light comes on.

Participant should start each trial with their feet in a comfortable stance and their arms relaxed at their sides.

A research assistant should be spotting the participant throughout.

Take a sitting break

*Gait (trial type: PD\_gait/ trial name: gait)*

Participant will walk on the treadmill for 3 minutes at a self-selected speed. EMG and movement data will be collected.

*Should have complete marker setup, foot switches, EMG on gastroc, hamstring, TA, quad*

Move treadmill into the collection volume under the safety support.

Instruct participant to step onto the treadmill.

Attach the cable to the safety harness.

Attach kill switch to subject's clothing.

Power up the treadmill.

Read the script to the participant, explaining the tasks.

Slowly increase the speed of the treadmill until the desired speed is reached. Record the final speed on the data collection sheet.

Once the participant has reached a comfortable gait begin data collection.

At the end of data collection, inform participant they are finished and then stop the treadmill (manually decrease the speed to zero).

Remove safety cable and assist the participant in stepping off the treadmill.

Take another subject calibration trial (should have two subject calibration trials- one for use with br, one for all others)

Take another force plate zero trial

#### Optotrak Data Key

Marker	Location	Columns
1	Right Thigh	2:4
2	Right Knee	5:7
3	Right Shank	8:10
4	Right Ankle	11:13
5	Right Heel	14:16
6	Right Toe	17:19
7	Left Thigh	20:22
8	Left Knee	23:25
9	Left Shank	26:28
10	Left Ankle	29:31
11	Left Heel	32:34
12	Left Toe	35:37
13	Right ASIS/Great Troch	38:40
14	Sacrum	41:43
15	Left ASIS/Great Troch	44:46

#### Pre Data Collection Tasks

##### *Recruitment:*

Once a participant has passed the health screen and is scheduled, send them a confirmation letter and directions to the lab.

If it is a PD participant, also email them to ask them to see Dr. Lyons within 3 months of the testing date. Attach the letter called "UPDRS Appt."

Email David to confirm testing dates/times.

##### *Misc:*

Email David Moore, parking guy, about reserving a parking meter. His email is [moore-ku@ku.edu](mailto:moore-ku@ku.edu) and phone number is 785-864-7293 (office) or 785-840-5693 (cell).

Make sure David Thomas has a parking pass for the week of testing. If there are 3 or more tests in a week it makes sense to get him a weekly parking permit. A red weekly visitor permit is \$8.00/week. Contact Mary Olson at KU Parking. I just sent an email to [kupark@ku.edu](mailto:kupark@ku.edu) and that is who responded to me. You can either pay for the permit and get reimbursed or ask them to invoice the ME department (specify that this is for Luchies's PD Pilot project so the office knows what it is). If there are 2 or fewer tests in a

week, it makes sense for him to just park in the parking garage and pay \$1/hour. In this case, we add the parking fee to his timesheet (there is a column for parking). Just note the number of hours he parked for. Email Kelly Lyons ([klyons@kumc.edu](mailto:klyons@kumc.edu)) to let her know if we are testing a PD patient so she can make sure and see them in clinic in case they happen to have an appointment before they come in for testing. Make sure the laundry is all clean (sheets, shorts, socks, etc).

### **Post Data Collection Tasks**

#### *File Backup:*

Take “PD Project Data Transfer” external hard drive from out of Molly’s desk and transfer the optotrak files to the hard drive.

Connect the video camera to the Labview computer and turn it on.

Connect the external hard drive to the Labview computer.

Copy the video and optotrak data to the appropriate folder in the Labview computer.

Copy all files from the labview computer folder to the “Master Backup Hard Drive” (the 1 TB one that sits on the desk by the labview computer) as well as on the PD Project Data Transfer hard drive.

Double check that you have complete sets of data on both the labview computer, the master backup hard drive, and the transfer drive.

Take the transfer drive home with you.

#### *DT Timesheet*

Update the spreadsheet “DT Timesheet” with the date and hours that he worked and any parking that we owe him for.

#### *Payment and Thank You’s:*

At the end of a testing week, collect all of the payment forms out of the folders of each participant.

Complete the back side of the forms, and take to Carl to sign.

Make copies of the signed forms for our records and turn in the originals to Leslie in the ME office.

Write and send a thank-you card from our lab to the participant.

#### *PD Patient Appt. with Dr. Lyons Record*

Dr. Lyons needs to know about each patient that we test and when we test them. Update the spreadsheet called “Testing Dates” to include each PD participant. Really this should be updated as soon as the patient is scheduled in case they go in to see Dr. Pahwa between scheduling and testing.

*PD Pilot Protocol: Checklist*

*Start Equipment Setup:*

- \_\_\_\_\_ Check camera positions
- \_\_\_\_\_ Turn on force plates, cameras, SCU
- \_\_\_\_\_ Verify force plates (channels 0-11,16-21), EMG (channels 22-29), pull device load cell (channels 12-13), gait initiation light (channel 14), and trigger (PFIO) are connected to DAQ board
- \_\_\_\_\_ Connect video camera
- \_\_\_\_\_ Connect pull device – normal (channel 12), shear (channel 13)
- \_\_\_\_\_ Balance force plates

*Start Subject Setup:*

- \_\_\_\_\_ Consent
- \_\_\_\_\_ Physical Screening
- \_\_\_\_\_ Clarify history (falls in previous 3 months, severity and duration, medication status)
- \_\_\_\_\_ Mini-mental exam
- \_\_\_\_\_ 5 Self-Report Tests

*Complete Equipment Setup:*

- \_\_\_\_\_ Complete Optotrak startup (registration, calibration)
- \_\_\_\_\_ Collect a FP zero trial for tracking drift (trial name: FPzero1)
- \_\_\_\_\_ Calculate appropriate weight for pull and load pull device (see paper)
- \_\_\_\_\_ Test Pull Device
- \_\_\_\_\_ Place “GO” switch box and target

*Complete Subject Setup:*

- \_\_\_\_\_ Measurements and EMG Placement
- \_\_\_\_\_ Optotrak markers
- \_\_\_\_\_ Put harness on
- \_\_\_\_\_ Put EMG belt on

*Data Collection:*

- \_\_\_\_\_ Connect markers and make sure they are all seen in Optotrak
- \_\_\_\_\_ Collect a subject calibration trial (static trial)
- \_\_\_\_\_ Check that movie camera is working
- \_\_\_\_\_ Check to make sure all markers are visible
- \_\_\_\_\_ Check EMG signal



Sway (trial name: sway1EO)

3 EO/3 EC Each test will last 30 seconds with 30 seconds of rest in between trials.

*Should have complete marker setup, EMG on gastroc, SOLEUS, TA, quads*

\_\_\_\_\_ Disconnect Solius EMG channel and connect to hamstring electrode

Balance Recovery (trial name: pull1)

3 Backward Pull Trials

*Should have modified marker setup (no sacrum or ASIS, but including great troch markers),*

*EMG on gastroc, hamstring, TA, quad*

\_\_\_\_\_ Change markers: move calf and thigh markers out of alignment with knee, ankle, and hip markers. Add a great troch marker if not already in place. Remove ASIS markers.

\_\_\_\_\_ Take a static trial for use with BR (w/troch markers)

\_\_\_\_\_ Put on the rigid belt

\_\_\_\_\_ Calculate weight drop height (8.7% of waist height) and adjust- measured from brushes

\_\_\_\_\_ Perform a total of 3 trials with 30 seconds rest in between trials

\_\_\_\_\_ Check each trial in Optotrak

\_\_\_\_\_ Remove belt

Gait Initiation (trial name: gait\_ini1)

5 trials, all starting from standing with one foot on each force plate

*Should have complete marker setup, EMG on gastroc, hamstring, TA, quad*

\_\_\_\_\_ Check each trial in Optotrak

Gait (trial name: gait)

Participant will walk on the treadmill for 3 minutes at a self-selected speed.

*Should have complete marker setup, foot switches, EMG on gastroc, hamstring, TA, quad*

\_\_\_\_\_ Take another force plate zero trial

\_\_\_\_\_ Make sure that you have two static trials

*Data Collection Sheet*

Date: \_\_\_\_\_ Time: \_\_\_\_\_ Subject #: \_\_\_\_\_  
Engineer: \_\_\_\_\_ Testing Order: \_\_\_\_\_  
Engineer: \_\_\_\_\_  
PA: \_\_\_\_\_

PD Duration: \_\_\_\_\_

PD Medications (list other medications on health screen):

Name: _____	Dosage: _____	Frequency: _____	Last Dose: _____
Name: _____	Dosage: _____	Frequency: _____	Last Dose: _____
Name: _____	Dosage: _____	Frequency: _____	Last Dose: _____
Name: _____	Dosage: _____	Frequency: _____	Last Dose: _____
Name: _____	Dosage: _____	Frequency: _____	Last Dose: _____
Name: _____	Dosage: _____	Frequency: _____	Last Dose: _____

*Fall History:*

Falls in previous 3 months:

Date: \_\_\_\_\_ Description: \_\_\_\_\_

Date: \_\_\_\_\_ Description: \_\_\_\_\_

Date: \_\_\_\_\_ Description: \_\_\_\_\_

Date: \_\_\_\_\_ Description: \_\_\_\_\_

Mini-Mental Score: \_\_\_\_\_

*Measurements:*

Height: \_\_\_\_\_

Weight: \_\_\_\_\_

Leg Length (ASIS to medial ankle via knee): L: \_\_\_\_\_ R: \_\_\_\_\_

Inter ASIS distance: \_\_\_\_\_

Knee Width (between femoral condyles): L: \_\_\_\_\_ R: \_\_\_\_\_

Ankle Width: L: \_\_\_\_\_ R: \_\_\_\_\_

Foot Width: L: \_\_\_\_\_ R: \_\_\_\_\_

Foot Length: L: \_\_\_\_\_ R: \_\_\_\_\_

Thigh Length (troch. to lat'l tibial plateau): L: \_\_\_\_\_ R: \_\_\_\_\_

Calf Length (lat'l tibial plateau to lat'l mall.): L: \_\_\_\_\_ R: \_\_\_\_\_

Ankle Height: L: \_\_\_\_\_ R: \_\_\_\_\_

Calf Circumference (largest pt.): L: \_\_\_\_\_ R: \_\_\_\_\_

Thigh Circumference (mid-thigh): L: \_\_\_\_\_ R: \_\_\_\_\_

Waist Height: \_\_\_\_\_

Weight loaded for pull device: \_\_\_\_\_

Drop distance for pull device: \_\_\_\_\_

Testing Notes:

EMG Check: \_\_\_\_\_

**Sway (30 seconds @ 1000Hz EMG/FP, 100Hz Opto)**

Need 3 EO and 3EC perfect trials

\*Most important data- force plates and EMG

Trial	Video File Name	Labview File Name	Optotrak File Name	Trial Notes
FPzero				
Sway1				
Sway2				
Sway3				
Sway4				
Sway5				
Sway6				

**Balance Recovery (5 seconds @1000 Hz EMG/FP, 100Hz Opto)**

Need 3 perfect trials

\*Most important data- force plates, EMG (TA), markers (up to knee, both sides), load cell channels, video

Trial	Video File Name	Labview File Name	Optotrak File Name	Trial Notes
FPzero				
Static				
Pull1				
Pull2				
Pull3				

**Gait Initiation (5 seconds @1000 Hz EMG/FP, 100Hz Opto)**

Most important data: force plates, gait initiation light, EMG (all), markers (all). Watch for a clean force plate strike on fp3 for the first step. If it is not a clean strike, the trial is not good.

Need 5 perfect trials

Trial	Video File Name	Labview File Name	Optotrak File Name	Trial Notes
FPzero				
Static				
Trial				
Gait_ini1				
Gait_ini2				
Gait_ini3				
Gait_ini4				
Gait_ini5				

**Gait (100 Hz Opto only)**

Most important data: Markers (all)- this is all we have for gait.

Trial	Video File Name	Labview File Name	Optotrak File Name	Trial Notes
Static		n/a		
Trial				
Gait		n/a		

*Parkinson's Study Scripts*

Postural Sway

***“For this set of tests you will stand here with your hands to your sides and have either your eyes focused on the picture in front of you or have them closed. We will do several trials with rest in between. I will tell you when to begin each trial and I will tell you when to relax.”***

**EO:**

Instructions to subject:

***“For this test, you will stand as still as possible. Focus your gaze at the target in front of you”***

**EC:**

Instructions to subject:

***“For this test, you will stand as still as possible with your eyes closed. Keep your eyes closed until the end of the trial.”***

Gait Initiation :6 trials start with feet on force plates and check for clean strike on back force plate (capture push off and first step)

Instructions to subject:

***“For this set of tests you will start standing still and then begin walking when you see the green light. Keep walking until I tell you to stop. You will take approximately 3-4 steps. We will do several trials with rest in between.***

Repeat for each trial:

***“For this test, you will stand here as still as possible and when you see the green light you will start walking forward, looking ahead while you walk.”***

Balance Recovery: 3-5 trials

Instructions to subject:

***“This study will let us look at your response to a balance disturbance. You will be asked to stand here on these force plates and a cable will be attached to your waist. The cable will pull you backwards and you need to regain your balance. We will have you repeat this several times. We will explain each step and give you a rest between trials.”***

***“First we will have you put on this waist belt, which will be attached to the cable that will pull you for each trial. For your safety, you will wear a safety harness. The harness will catch you if you are unable to regain your balance.”***

***“Now, we will have you place your right foot on this plate and your left one on this plate. Stand comfortably with your feet approximately shoulder-width apart. Please stand quietly with your hands at your sides. Please remain as still as possible before and after you regain your balance, until I tell you to relax. Do you have any questions?”***

***“Okay, now we will start the test. Please remember to stand up straight and remain still before the pull and after you step.”***

Gait: 1 trial

Instructions to subject:

***“For this test you will walk on this treadmill for approximately 3 minutes at a pace that is comfortable for you. First we will determine a pace and then the test will begin. Again, you will wear a safety***

*harness that will catch you in the event that you lose your balance. Also, if at any time you feel uncomfortable, you can push this button and the treadmill will stop abruptly.”*

*“First, we will start the treadmill slowly and choose a speed that feels like a comfortable, normal walking pace to you. Do you have any questions?”*

*(Choose pace)*

*“Now, we will start the test. Just continue to walk normally. The test will last approximately 3 minutes.”*